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AGARDograph No. 255

Advancement on Visualization Techniques

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARDograph No.255

ADVANCEMENT ON VISUALIZATION TECHNIQUES

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This AGARDograph was prepared at the request of the Guidance and Control Panel of AGARD.

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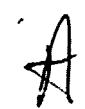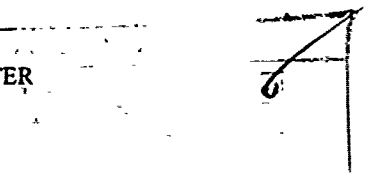
PREFACE

Visualization was not much of a problem for pilots of the very first powered aircraft. They sat out in the wind stream with a broad view of the terrain. Operations were conducted during daylight in clear weather. The flights were low and slow. The information which was needed for control of the vehicle came from observation of the visual scene. With time, aircraft flew higher and faster, at night and in bad weather. Military aircraft became weapons platforms and pilots required more and more information to do their job. The pilot was enclosed in a cockpit and the cockpit was filled with instruments to provide the information to him. The amount of information which the modern military pilot needs has grown enormously. But the size of the cockpit and the pilot's human sensors have remained more or less the same. As a result there has been a constant search for better ways to present to the pilot the large volume of information which he needs to carry out his mission. Much of the added information needs to be related to the same broad view of the terrain which was the primary input for the earliest pilots. In some cases the outside visual scene has to be recreated because the pilot's outside visual references have been obscured. In other cases it is desirable to have new information appear superimposed on the visual outside scene properly correlated with reality. Techniques for providing the pilot visualization have grown rapidly. Technology has developed from mechanical gauges through electro-mechanical instruments to electronic displays.

Today the cathode ray tube has become the standard electronic display device. There are several in almost all new aircraft. It has great versatility, but is bulky, requires high-voltage power supplies and is not ideally suited to the bright ambient light encountered in cockpits. A number of new technologies for displays have been developed and have found increasing civil markets especially in the calculator and watch industries. These are sometimes referred to as "flat panel displays". They include liquid crystal, light emitting diodes, electroluminescent displays and gas plasma panels. There are others still in the research stage or in development for limited commercial purposes. Many have the potential for producing flat panel analogues of the cathode ray tube. Some are now finding applications in military cockpits.

Despite the rapid growth in the field of visualization and display in aircraft cockpits, there is no current textbook which describes the technology and those basic principles which provide a foundation for someone interested in this area. The purpose of this AGARDograph is to provide some of the basic principles and at the same time report on recent developments which contribute to the state of the art. The subject matter is focused broadly on principles, technology and applications. It is hoped that it will be of value to both the expert in the field as well as the newcomer who seeks to find out what cockpit displays are all about.

It is a pleasure to acknowledge the many persons who have made the publication of this volume possible. First recognition should go to Mr John Hollington of the Guidance and Control Panel who made initial contact with authors and organized the contributions from the United Kingdom, which constitutes at least half of the document. The support of past Panel Chairman, Mr Morris Ostgaard, who initiated the topic, and Mr Peter Kant, who provided guidance, has been invaluable. Other Guidance and Control panel members' help in obtaining authors was greatly appreciated. The interaction with Prof. Ir. D.Bosman and the members of his Avionics Panel Working Group on "Modern Display Technologies and Applications" was very helpful. Colonel J-C. de Chassey, Guidance and Control Panel Executive, provided outstanding administrative support throughout the effort. The secretarial assistance of Mrs Marks of M.I.T. was crucial to preparation of several of the manuscripts. Finally, the willing and enthusiastic contribution of the individual authors is recognized as the most important element of the total work. My sincere thanks to you all.

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Editor

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THE PRESENTATION OF STATIC INFORMATION ON
AIR TRAFFIC CONTROL DISPLAYS
by
R.J.G. Edwards*

DISPLAY SYSTEM PERFORMANCE

I.1 DESIGN PARAMETERS

It is assumed that the system objectives and display
system design concepts have already been set and what remains
to be done is to define the physical characteristics of
the display consistent with human performance. Eight
display characteristics have been selected as critically
important [50], they are:

1) Frame Rate

2) Contrast Ratio

3) Ambient Illumination

4) Symbol Characteristics

5) Resolution

6) Bandwidth

7) Registration

8) Phosphor Type

The exact priority of each characteristic and the
specific result of their interrelationships is a function
of the particular application and so will be considered
with respect to an ATC display environment.

I.1.1 Frame Rate

This is the speed in Hertz with which a displayed
image is updated. It is of primary concern because of its
causal relationship with flicker, which is the fluttering
or flashing sensation caused by picture brightness altera-
tions. Above a critical flicker frequency (CFF) usually
considered to be 30-35 Hz, flicker is no longer perceptible.
The primary determinants of flicker are:

1) Frame rate

2) Brightness

3) Ambient illumination

4) Phosphor

5) Visual angle subtended by the display

6) Amplitude and waveform of the
   variation

7) Location of stimulus on the
   retina (peripheral vision is
   more sensitive to this phenomenon).

*This was extracted from Volume II of Dr. Edward's
PhD thesis written at the Cranfield Institute of
Technology and made available through the courtesy
of Professor John Shepherd.

Long persistence phosphors have relatively low brightness modulation and hence relatively low frame rates are required to prevent flicker. Figure I.1 shows CFF versus brightness [10] and it is worth noting that below approximately 18Hz a residual flicker is inevitable, so there is little point in attempting to eliminate flicker in any type of raw radar display unless the antenna scanning rate exceeds 18Hz which is only feasible in very short range radars such as are used for ground movement surveillance.
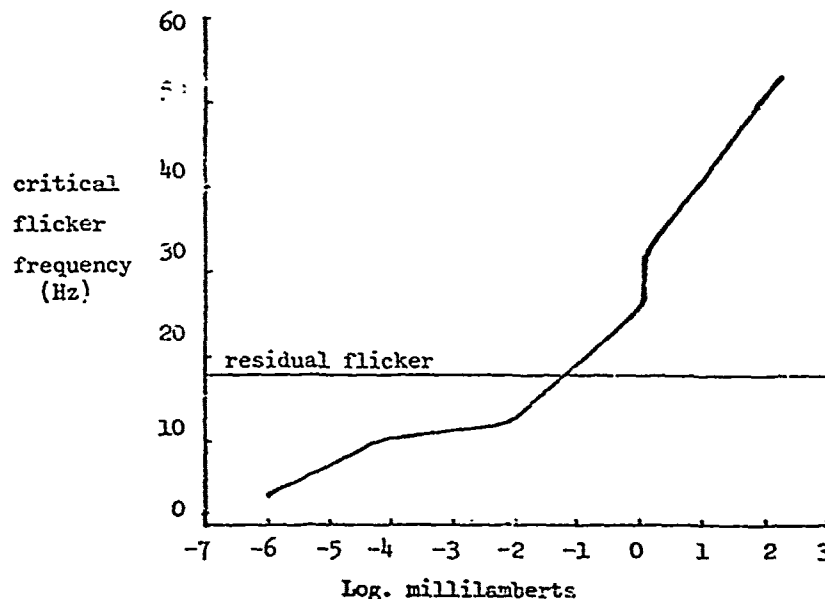
Figure I.1 Critical flicker frequency at various brightness levels.

Frame rate for a given display is a function of the following factors:

1) Volume of information per frame

2) Ambient illumination

3) Phosphor

4) System storage capability

5) System write/erase speed

6) Bandwidth

7) Display control techniques.

In most surveillance raw radar displays the last factor is limiting.

I.1.2 Contrast Ratio and Ambient Illumination

Contrast ratio is expressed as the ratio of maximum to minimum luminence:

$$CR = \frac{B_{max} - B_{min}}{B_{min}}$$

The optimum contrast ratio for a display is linked to the ambient illumination. Although the range of brightness over which the human eye adapts is very large, the minimum contrast ratio required for discrimination of two adjacent [102] areas on a display is about 2:1. Military standards normally specify a minimum of 10:1.

The definition of contrast ratio for light producing displays where the writing is brighter than the background may be expressed as:

$$C_t = \frac{B_s + B_w}{B_s}$$

B_s is the brightness of the screen from ambient light

B_w is the brightness of the written line when ambient light is excluded.

Contrast ratios may be enhanced by use of filters which reduce the reflected ambient light but these techniques usually suffer from the drawbacks of reduction in luminance and additional symbol blurring.

The following factors have a direct effect on contrast ratio:

1) Display brightness

2) Symbol brightness

3) Ambient brightness

4) Phosphor

5) Type and nature of ambient light source

6) Viewing geometry

7) Shields, filters, etc.

The long persistence phosphors used in raw radar displays have low optical efficiency and the low brightness of these displays dictates a commensurately low ambient light level to preserve an acceptable contrast ratio and maintain target detectability levels.

I.1.3 Symbol Characteristics

The legibility of symbols and alphanumeric characters is a function of the following factors:

1) Viewing geometry

2) Resolution

3) Method of symbol generation

4) Symbol style

5) Symbol aspect ratio

6) Line spacing

7) Registration accuracy.

If these factors are not optimised with respect to symbol legibility, two related effects may occur:

(a) *Confusion* is known to occur with certain alphanumeric formats even under optimum display conditions and the confusion ratio will rise as the display departs from optimum especially with regard to complex groupings of symbols.

(b) *Clutter* is the overabundance of information and is one of the major problems in modern display systems. In a raw radar display clutter may take the form of noise and false target returns which mask the "real" returns, however the problem has expanded so that on modern displays it consists of being able to discriminate the required information from the vast amount of data displayed.

I.1.4 Resolution

This term is not easily defined and is generally a function of display type, the method of generation and often the training of the designer. In general it may be thought of as the smallest distinguishable display element separation. Resolution is variously defined as:

1) the size of a focussed electron beam spot on the phosphor screen

2) seconds of arc, the angular measure of the smallest observable spot in a given pattern

3) graininess, the irreducible size of the display medium grain or element

4) lines per unit distance.

For a given display type the resolution achieved is a function of:

1) Frame rate

2) Contrast ratio

3) Phosphor

4) Symbol characteristics

5) Bandwidth

6) Display brightness

7) Viewing geometry.

Spot shape effects size and therefore resolution. The spot size is generally expressed according to the "shrinking raster" definition, that is the distance between two points on opposite sides of the centre, at which the brightness is half that of the centre.[103] In displays where the spot is scanned in a rectilinear manner producing a raster scan pattern, resolution is expressed by the number of line-space pairs per unit linear dimension.

Within the limits described above, the resolving capability of the eye (about 40 lines per degree of arc) determines the minimal resolution levels for the display and optimum performance is generally achieved when symbols resolve between 12-15 minutes of arc or 10-12 lines.

Digital display resolution may be simply defined as the minimum addressable element size and may, of course, vary in different directions, depending upon the shape of the display element. General purpose alphanumeric displays such as the Digisplay [104] which employs an electron beam excited phosphor screen or the plasma panel as described in Appendix II.2, have square or circular cells so that the display element produced gives isotropic resolution.

I.1.5 Bandwidth

The specification of bandwidth is basic to any display system as it describes the available resolving power of the system and is interdependent with:

1) Frame rate

2) Resolution

3) Symbol characteristics

I.1.6 Registration

The superimposition of multiple images to form a composite single image requires that the component images register. Misregistration is failing to correctly overlay the images and may be caused by geometric distortion or by improper direction or alignment of the system. 100% stroke-width misregistration means the images are just beside each other. Registration considerations are of primary importance as information density increases and with pre-formatted textural, multi-colour, or complex overlaid displays.

Registration accuracy is determined by:

1) Resolution

2) Symbol characteristics

3) Display hardware characteristics
   (gun type, deflection techniques, etc.)

4) Programming accuracy (in computer
   driven displays).

While most displays are capable of registration accuracy of 0.1% screen width, system requirements may not require such close tolerance, from the human performance point of view an acceptable value is 50% strokewidth.

I.1.7 Phosphor type [105,106]

Screen efficiency, decay time and colour of the phosphor are important characteristics and the last two particularly, have direct bearing upon the performance of the human operator.

Decay time, or persistence is directly related to the CFF and is thus related to the required frame rate. The persistence needs to be long enough to eliminate flicker but short enough to stop smearing or ghosting of previous information. Short persistence phosphors are

suitable for high refresh rates, medium persistence phosphors are used on most computer graphics displays and long persistence phosphors are generally used for raw radar where the refresh rate is low. Those phosphors emitting in the middle of the visible spectrum are preferable to those emitting at the blue end due to human visual capabilities [107].

Phosphor selection affects:

1) Resolution

2) Contrast ratio

3) Frame rate

4) Write/Erase speed

5) Brightness

6) Ambient illumination

Phosphor mixtures have been produced to give special characteristics for mixed raw and synthetic radar and to facilitate light pen operation.[108] The characteristics of these and other commonly used phosphors in ATC displays and flying spot scanners are given in table I.1. The fluorescent colour code used in the table is as follows:

B – blue   O – orange
G – green   R – red
IR – infra-red   Y – yellow

When describing persistence the common ranges are:

Very long   – > 1s
Long   – 100ms to 1s
Medium   – 1ms to 100ms
Medium short – 10μs to 1ms
Short   – 1μs to 10μs
Very short   – < 1μs

The discussion of phosphor types thus far has implied a CRT display however the concepts involved may readily be extended to include similar properties of other display types. Electroluminescent panels employ phosphors which may be described in exactly this way. Decay time or persistence is a property of all the displays considered in section 2.2. The LED and liquid crystal displays have extremely short persistence whereas the intrinsic memory of the plasma panel may be classed as infinite persistence.

I.2 CHARACTERISTICS REQUIRED OF EFFECTIVE DISPLAYS.

1) Individual characters highly legible

2) Meaningful groups of characters easily recognised

3) Characters readily discernible from each other

4) Weak signals detectable at all display range scales

5) Display can be viewed equally well from any required viewing angle

Type	Colour	Peak wavelength or range (nm)	Persistence to 10% unless shown	Application
B	B/O	450 and 590	1us and 250s *	Radar display
B2	B/O	450 and 590	1us and 4s	Visual display with light pen
B5	YG/O	520 and 590	1s and 250s *	Raw radar with SSR labels
C3	YG to R	530 to 620	2.4 and 1.5ms	Penetron – green high
C4	R to YG	630 to 515	1.0 and 0.2ms	Penetron – red high
H	O	590	250s *	Long range raw radar
H2	O	590	100s *	Fine grain version of H
H4	O	600	150s *	Burn resistant version of H
J	B/YG	450 and 520	1us and 20s *	Medium range raw radar
J2	O	590	40s *	Medium range raw radar
J6	B/YG	470 and 550	3.5s	Short range radar
K	YG	540	500ms	Synthetic radar displays
K3	O	580	200ms	Synthetic radar displays
K8	YG	520	1s	Synthetic radar
K9	YG	520	200ms	Anti-flicker for rear port tubes
L	O	590	70s *	Medium range raw radar
L2	O	590	30s *	Medium range raw.radar
L3	O	590	4s	Computer display-anti-flicker
P1	YG	520	25ms	Synthetic radar
P7	see type J			
P12	O	590	~100us	Synthetic radar
P19	O	590	~1s *	Short range radar

Table I.1 Characteristics of phosphors commonly used in ATC displays

Type	Colour	Peak wavelength or range (nm)	Persistence to 10% unless shown	Application
P21	RO	400-700	~ 100ms	Synthetic radar
P24	G	500	~ 400ns	Flying spot scanner
P26	see type H			
P28	see type K			
P31	G	530	3µs	High efficiency
P32	see type J6			
P33	see type L			
P34	G	490	~ 40 sec (variable)	Persistence stimulated with IR
P36	YG	470-670	250ns	Flying spot scanner
P37	B	450	300ns	Flying spot scanner
P38	see type L3			
P39	see type K8			
P40	YG	400-600	~ 100ms	Integrating phosphor
P42	YG	520	~ 100ms	Anti-flicker (P31 + P39)
P47	B	400	140ns	Flying spot scanner
Q8	see type P47			
S	see type P31			
Y	see type P34			

* Note: Persistence to 1% (applies to long component only of B, B5, J)

Table I.1   Characteristics of phosphors commonly used in ATC displays   (continued)

6) Minimum fall off in screen brightness

7) Maximum contrast

8) Minimum image distortion

9) Fast observer response time.

10) High observer accuracy

11) Minimum flicker

12) Minimum response time in complying with user requests

13) Display parameters (e.g. brightness) adjustable by user.

I.3 COLOUR DISPLAYS

The colour display designer is concerned with radiant power in the visible range with a spectral distribution which elicits a given sensation of colour when viewed by an observer. In colour reproduction systems such as colour television, the aim is to make the colour sensation correspond to that which the viewer would have if presented with the original scene. In other instances, such as ATC displays where colour is intended primarily as a coding device, the reproduction requirement is absent but the aim is still to produce a particular colour sensation at a given spatio-temporal position on the display. Economical representation of colour information reduces transmission and storage costs. The chief property which allows such economy is the *trichromatic* nature of colour vision [109] which enables any colour to be specified as a mixture of three primary colours or *primaries*. Any three colours may be used as primaries so long as none is simply a mixture of the other two. Red, green and blue are commonly used but others are possible.

I.3.1 Colour Characteristics

Colour sensation can be defined by three attributes,

Luminosity is the apparent brightness representing the total visual energy of the colour light.

Hue is the visual effect of colour determined by primary components which lead to the subjective discrimination between colours.

Saturation is a subjective of the purity of a colour. If it is "pale" or "whiteish" it is said to be unsaturated.

I.3.2 Colour Perception

The human eye perceives colour depending on the following factors:

1) luminance

2) wavelength

3) adaptation

4)   duration of light stimulus

5)   image size

6)   ambient illumination.

The sensitive elements of the eye are made up of cones and
rods and their distribution varies over the area of the
retina. Colour sensation and high resolution is achieved
by a central concentration of cones in the foveal region.
The cones are most effective at normal light levels, above
1 ftL, giving photopic vision and are most sensitive to a
yellow-green hue of 550nm wavelength. The rods are more
sensitive than the cones at low light levels but give poor
resolution and have a longer adaptation period. Scotopic
vision occurs at light levels below 10^{-5}ftL with maximum
sensitivity to a bluish-green hue of 510nm. These light
levels are extremely low and would not be encountered in
an ATC display environment.

I.3.3   Colour Measurement

Colour sensation may result from several different
simultaneous visual stimuli. The dominant wavelength may
be measured by obtaining a combination of the three
primaries which are said to match the given colour by
observers with normal colour vision. Using the red, green,
blue (RGB) system of primaries it may be necessary to use
negative coefficients (r, g and b) of one or more primaries
since the colour may lie outside the RGB triangle shown in
Figure I.2. This is confusing as a negative primary is
not realizable and can make the calculations difficult to
handle. The problem may be overcome by adding a known
amount of one primary to the unknown so bringing it within
the RGB triangle.

The XYZ system of primaries accepted as the inter-
national standard by the Commission Internationale de
l'Eclairage (CIE) with coefficients x, y and z avoids these
problems by enclosing the entire spectral locus. The
diagram shown in Figure I.3 shows the "equal energy"
spectrum in which the luminance of every colour is the same.
A point marked "C" represents the co-ordinates of standard
illuminant white light. The dominant wavelength of a given
colour may be measured by drawing a straight line from C
through the given colour co-ordinates to cut the spectrum
locus. The point of intersection indicates the dominant
wavelength.

Absolute colour measurement is generally made in
terms of the CIE chromaticity diagram where x and y
uniquely define the hue (dominant wavelength) and satura-
tion (purity) of any visible radiation. Three standard
filters with tristimulus values $\bar{x}$, $\bar{y}$ and $\bar{z}$ are used and
the emission spectrum of a known source passed through these
to give X, Y and Z directly, the chromaticity co-ordinates
x and y are then defined as:

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

and these values for the spectrum are plotted to give the CIE chromaticity diagram shown in figure I.3.

In practice the situation is slightly complicated because:

1) $\bar{x}$ response cannot be achieved by one filter, so two are used $\bar{x}$ (blue) and $\bar{x}$ (red)

2) Both $\bar{x}$ and $\bar{y}$ are difficult to match at the end of the spectrum requiring the use of $-\bar{x}$ and $-\bar{y}$ filters to compensate

3) Filter density is not easily controlled so the photometer reading must be multiplied by a constant to derive X, Y and Z.

In practice the light passing through six filters is measured giving:

$$X'_R, \; X'_B, \; Y', \; Z', \; X'' \text{ and } Y''$$

then

$$X = 2X'_R + 0.75X'_B - 2X''$$

$$Y = Y' - Y''$$

$$Z = k.Z'$$

where k is determined for the particular colorimeter. x and y may be calculated as before. Figure I.4 shows the basic layout of a colorometer which may be calibrated using known filters and light sources.

I.4 ASSESSMENT OF DISPLAY SYSTEM QUALITY

The user will judge the quality of an interactive display system essentially from two characteristics:

1) usefulness of the information presented and

2) system response time when he wants to change the picture content.

The usefulness of information is a function of data content, layout and legibility and these may be arrived at by analysis of the user's mental process with regard to the environment and what problems he solves with which information.

The response time to be useful must measure the time from the moment the user realizes the need for some reaction from the system to the moment he becomes aware of the answer. What response time is acceptable depends upon many factors [54] including workload, urgency and type of task. The interaction mechanism must be as simple and natural as possible and should function in the terms in which the user thinks thus avoiding as far as possible the need for him to interrupt his train of thought. The response time achieved depends upon the distribution of workloads throughout the system so that system functions must be implemented with thought to the workload involved, frequency of use and the resulting build-up of queues within the system.
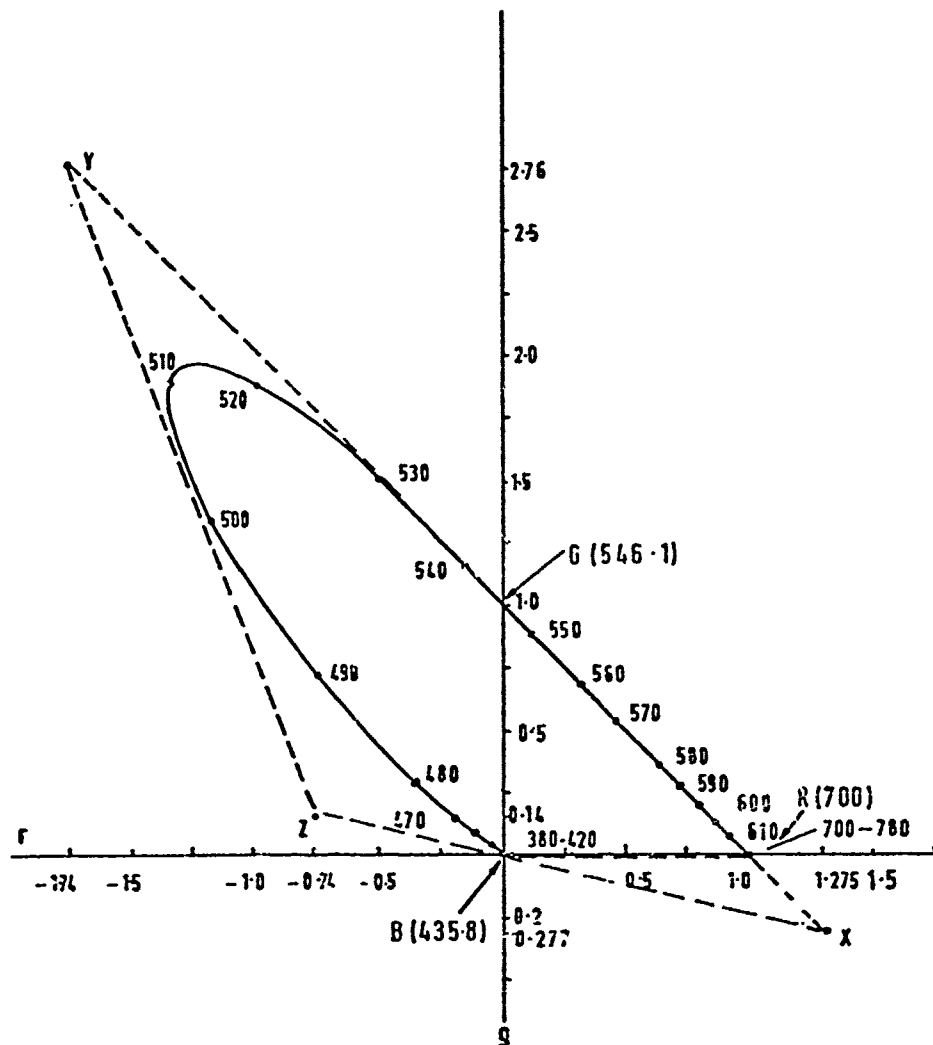
Figure I.2   The relationship between the axis of the CIE
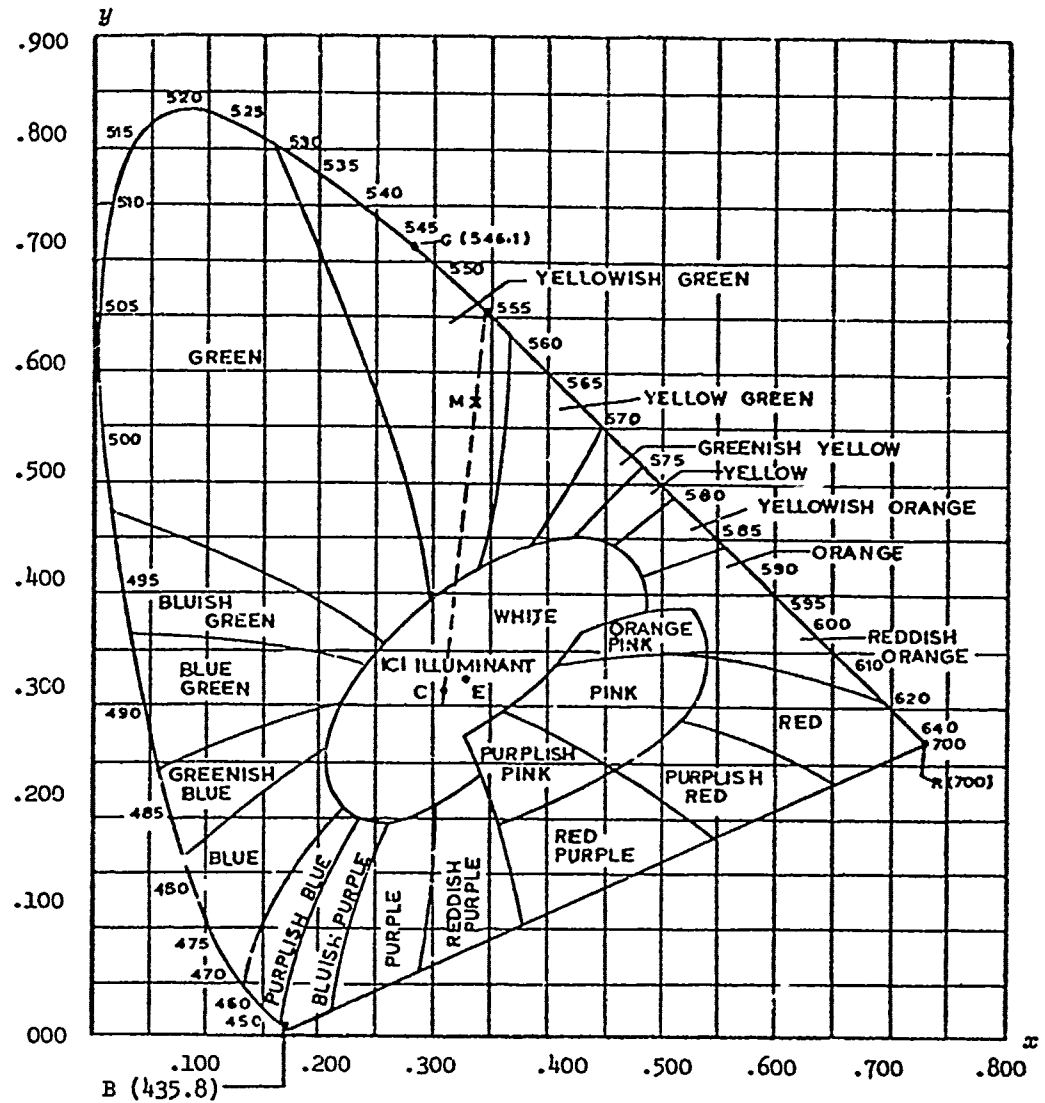   primaries (XYZ) and the spectral primaries (RGB)
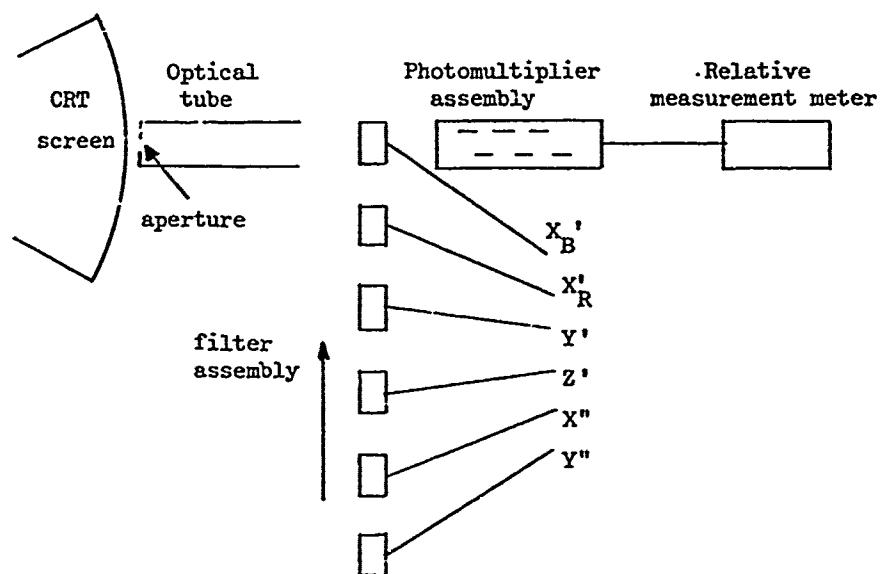
Figure I.3   Chromaticity diagram

Figure I.4   A method of measuring colour CRT luminance

I.5 MATRIX DISPLAY PRINCIPLES

The use of matrix techniques to connect elements of a
digital display makes a considerable saving in terms of
driving circuitry in some respects but also introduces a
number of complications. In the following discussion it
will be convenient to designate the rows and columns of the
display as a, b, c .... and p, q, r ... respectively.

I.5.1 Selection techniques

An element is selected by applying a suitable signal
between one of the row and one of the column leads. An LED
display has elements with diode characteristics and suffers
no problems as current may only follow one path through the
selected element as all other parallel paths contain reverse
biased diodes which present a high impedance.

If the display elements have a linear resistive or
capacitive characteristic a number of alternative current
paths may cause partial selection of unaddressed elements
which degrades the display resolution. Two methods of
addressing the display reduce this effect.

Half selection is the most common method of address-
ing a matrix display and is illustrated in figure I.5. Half
the required voltage is applied to the row while the other
half is applied to the column, all other rows and columns
are held at zero potential thus only half the selection
voltage appears across any unaddressed element in the same
row or column as the addressed element. If the display
elements exhibit a sharp threshold that is they are fully
"on" at any voltage above the threshold and fully "off" at
any voltage below then it is easy to arrange for half the
drive voltage to be less than the threshold. However, where
the elements have no threshold as is the case with liquid
crystals, half selection of the elements will cause a cross
to be displayed.

Third Selection involves connection of unaddressed
rows and columns to ±V/3. This results in one third the
full drive voltage being applied to unselected elements
giving improved discrimination and hence resolution as
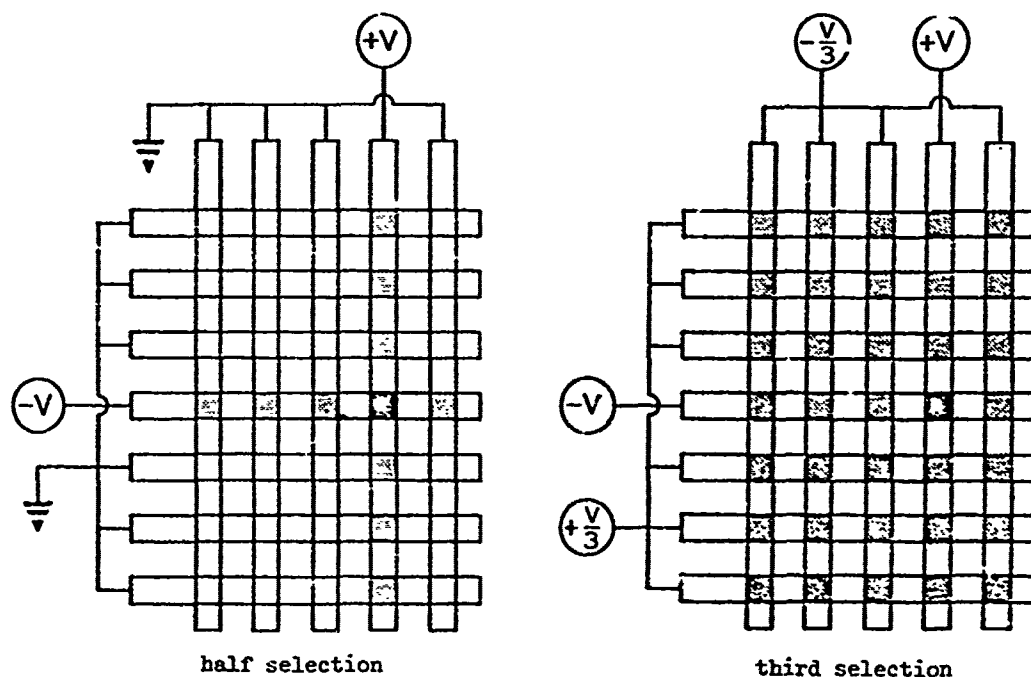shown in figure I.5.

half selection   third selection

Figure I.5 Selection techniques applied to matrix displays

I.5.2 Multiplexing

In a practical situation many elements will be addressed simultaneously and this introduces another complication in that addressing elements ap and bq will also select elements aq and bp.

This can be overcome by scanning the display so that it is built up row by row or column by column. Consider this technique applied to a 7 x 5 matrix, when the display is scanned a signal is applied to each row in sequence and appropriate columns are energised synchronously. Each row driver may energise up to 5 elements at a time with a duty cycle of 1 in 7, while each column driver energises only one element at a time, this must be considered when designing the drivers.

The scanning frequency must be high enough to avoid flicker. The ideal display element should have a fast rise time and slow decay time to cope with duty cycles in the order of 1 in 7 and in general decay time is the limiting factor in the number of rows which may be scanned.

If the display frame time is T and the number of lines scanned is n, then the "on" time of any element is at most T/n, thus for a rise time of τ_r and decay time of τ_d we have:

$$\tau_r < T/n \text{ and } \tau_d > T$$

These relationships are modified somewhat if one considers the integrating effect of a number of addressing cycles, they do however form a useful basis for considering display phenomena.

I.5.3 Circuits

To exploit the economical MOS range of integrated circuits the drive requirements must be kept below ~ 25V and this criterion can in general be met by liquid crystal devices. Below 5V TTL may be used though this is no advantage in liquid crystal displays as the current capability is wasted, LED displays, however, are ideally suited to this circuitry. For lowest possible power dissipation, drive levels in the order of 1-2 volts are being aimed at.

DISPLAY CHARACTERS

II.1 CHARACTER FONTS

Although the human operator is unsurpassed for character and pattern recognition, interpretation time and error rate will increase if the character is poorly formed. *Legibility* is a measure of the observer's ability to minimise these parameters while the term *readability* is used to imply consideration of the ability of the observer to read accurately words or code groups and this is affected by such factors as character spacing and the relative shapes of characters when presented in groups. Much work has been done on the design of suitable alpha-numeric fonts which improve both legibility and readability.

The European Computer Manufacturers Association (ECMA) has accurately specified a character set [111] which is as legible as any proposed or existing typeset. It must be remembered, however, that the method of generation can have a substantial effect on the ultimate presentation so that modifications may be necessary to restore legibility when certain generation techniques are employed. Figure II.1 illustrates the effect of the various generation techniques which will be considered in the next section on a character from the OCR B character set.

The upright Leroy font is used in many stroke writing computer graphics displays but this is prone to confusion amongst ·certain members of the character set, it has been improved however and versions known as the Improved Leroy and the Lincoln/Mitre fonts are now used.

II.2 GENERATION TECHNIQUES

A variety of character generation techniques are available for the CRT display and as this device still commands a considerable portion of the ATC display market these techniques will be considered in more detail. All forms of digital display which employ matrix addressing rely on the dot matrix character solely.

The ECMA-OCR B character set is based on a constant line width and therefore poses minimum problems in reproduction on a CRT screen. Two classes of character generation will be considered:

Cursive

Flag
Circle
Discrete stroke

Beam Brightening

Dot matrix
Charactron
Monoscope

II.2.1 Cursive character generation

The parameters of the cursive generator which govern its ability to reproduce a given font are its *resolution* and *bandwidth*. The resolution is a function of the size of the matrix used to specify the turning points of the lines and the maximum number of strokes used to draw the character, while bandwidth is related to the writing speed and distortion so caused. Writing a 16 stroke character in 2μs calls for a 120ns clock rate which means a broad-band deflection system is required if character distortion is to be avoided. However too high a band-width leads to increased noise and jitter. If, with the parameters cited a compromise band-width of 8MHz were used serious character distortion is still evident and the most effective means of overcoming this is to "pre-distort" the character so as to optimise its final appearance. This procedure unfortunately increases the difficulty in designing the font and as a last resort, reduces to designing each character empirically on a "cut-and-try" basis.

Flag generation approximates the symbol with horizontal and vertical line segments and is the least flexible of the techniques, it does, however, simplify the driving electronics and is suitable for limited alphanumeric presentation.

Circle and stroke characters require a circular arc
generator which may not be readily available in all display
systems. However, if available, this technique produces
characters of superior quality to the discrete stroke variety
with, in general, fewer data words required in their description
therefore reducing the computer workload. Circular arc
generation is considered further in Appendix VIII.

Discrete stroke is the most commonly employed technique
on computer graphics CRT displays. A typical character would
consist of 16 strokes drawn on a 32 x 32 matrix of connection
points with generation times ranging from 1 to 10μs.

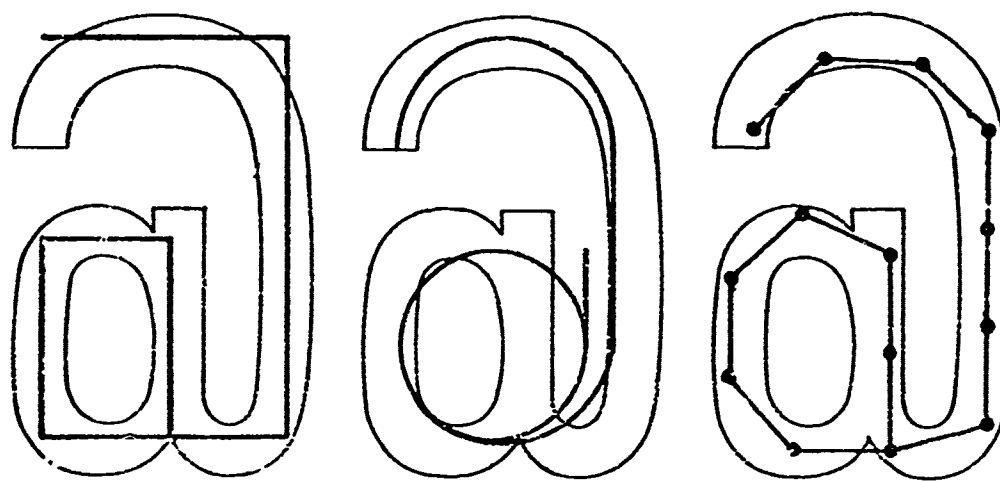### II.2.2 Beam brightening character generation

These techniques all require some form of raster scan
which is intensity modulated in order to achieve the desired
character. Sequential selection of either rows or columns
in a digital matrix display forms the "raster" while the
"beam brightening" signal is applied to appropriate columns
(or rows). This form of digital addressing does have its
drawbacks, however, and these were discussed in Appendix I,
section 5.

Dot matrix character generation necessarily requires
a rectilinear or TV raster and is particularly well suited
to EDD usage. Hardware character generators are available [112]
and the cost of these display systems has been brought down
to such a level that no other technique can compete where
only alphanumeric data is required on the display. A matrix
size of 5 x 7 is used where a cheap display requiring no
special characters is needed, however a 9 x 7 matrix gives
improved legibility and greater flexibility for special
characters and is considered necessary for ATC EDD applica-
tions.

Charactron generation or the *shaped-beam* tube involves
a mask incorporated into the CRT through which the main
electron beam is extruded in the shape of the required
character. Further deflection then positions the character
appropriately on the screen. Although this is the fastest
technique to be described, it does have limitations in
deflection angle if the shape of the character is to be
maintained. It does, however, share with the monoscope in
having very high resolution and is thus inherently capable
of extremely good characters.

Monoscope character generation involves raster
scanning of the individual characters which are "drawn" on
a special surface within the monoscope tube. Traditionally
the video output from the monoscope·is generated by secondary
emission from metallic characters and is reproduced as the
display screen is scanned synchronously. Advances in
electron beam diode switching technology have led to the
development of a new solid state target monoscope [113].
The device utilizes a character array produced by photo-
lithography on a silicon wafer to form diffused junction
diodes and an electron beam selectively scans the characters.
Life expectancy is considerably better than that of the
secondary emission monoscope and signal to beam current
gains of 2 to 3 orders of magnitude are achieved.

This technique has the unique property of allowing
character scanning by any form of raster which means it is
potentially usable as a real time character generator on a
raw radar display for alphanumeric information where a
polar raster is employed. It is not so attractive for
computer displays as the minimum generation time is in the
order of 10μs.

Flag   Circle and Stroke   Discrete Stroke
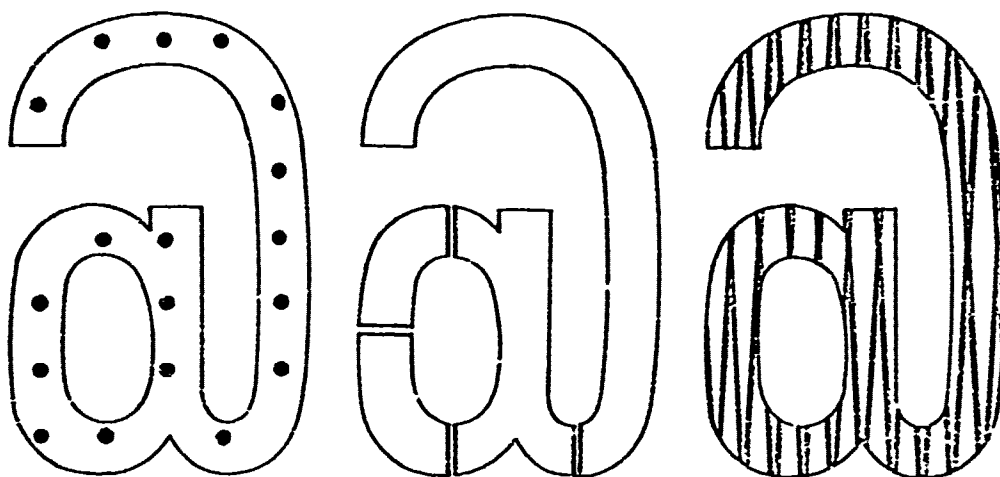
Cursive

Dot Matrix   Charactron   Monoscope

Beam brightening

Figure II.1   <u>Cursive and beam brightening character formation</u>

1-20

OPERATING PRINCIPLES OF COMMON DISPLAY DEVICES

III.1 THE CATHODE RAY TUBE

An electron gun situated in the neck of the tube illustrated in figure III.1 directs a stream of electrons towards a phosphor coated glass screen. The phosphor emits light when struck by the high energy electrons in the beam. Electron optics are used to focus the beam into a fine spot which is then positioned on the screen by a deflection system.

Figure III.1   The cathode ray tube

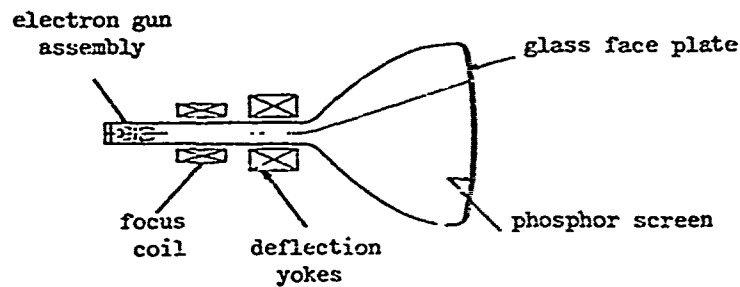*Focus* of the beam is achieved either electrostatically or electromagnetically with the latter generally giving better resolution, however deflection de-focussing is more severe with this technique. Resolution generally varies across the screen, being best at the centre and is typically 1000 to 1500 lines across a 50cm screen with spot size of 0.3 to 0.5mm. Laminar beam CRTs [114] have been constructed and give very high resolution as the spot is an image of the hole in the cathode assembly. Linear electron distribution rather than gaussian, gives very sharp spot edges and hence high apparent resolution. Geometric and deflection defocussing is also reduced.

Deflection can be either electrostatic or electromagnetic with the latter being more common in larger displays as it offers wider deflection angles and thus reduced tube length. Also lower voltages are required in the deflection circuitry.
Printed circuit coil techniques produce high accuracy repeatable deflection yokes. Early raw radar displays had a rotating yoke which was synchronised with the aerial scan and driven with a saw-tooth deflection waveform. Modern displays however employ orthogonal coil systems and the saw tooth is modulated by the sine and cosine components of the rotation frequency. The deflection angle of an electron beam passing through a magnetic field is given by:

$$\sin \theta = H.L \quad \frac{1}{2V_b} \cdot \frac{e}{m}$$

θ is the deflection angle,

where: H the magnetic flux density
L the length of the magnetic field,
V_b the electron beam potential,

and $\frac{e}{m}$ the electron charge/mass ratio

Boundary effects at the ends of the deflection system cause defocussing of the spot towards the perimeter of the screen. *Pin cushion* distortion is caused by interaction of the X and Y axis deflection fields and may be compensated in the coil drive signals or by shaping the field.

Electrostatic deflection requires a field set up between plates either side of the electron beam and the deflection angle is given by:

$$\tan \theta = \frac{\varepsilon.L}{2V_b}$$

where ε is the electric field strengh between the plates,
    L the length of the deflection field,
 and V_b the electron beam potential.

The deflection angle is inversely proportional to beam potential so deflection sensitivity may be improved by employing *post deflection acceleration* (PDA) allowing the beam to be deflected while still at relatively low potential.

Typical electromagnetic deflection systems will transit the tube diameter and settle in 15µs whereas electrostatic systems can achieve times as low as 2µs.

Phosphors are considered in more detail in Appendix I. For raw radar displays, the integrating effect of long persistence phosphors is used to enhance target detection and provide history information. For computer driven displays with high refresh rate, short persistence phosphors are used. Some phosphors have an initial high intensity very short duration flash or fluorescent emission before the phosphorescent emission. This fluorescence, usually blue or ultra-violet in colour, may be used to activate a photosensitive device such as a light pen [115] for position designation.

Colour CRT displays offer the advantages of a further coding parameter in ATC applications. The most common colour CRT is the *shadow mask tube* which is used in commercial colour television. The screen consists of a matrix of phosphor dots consisting of three primaries, usually red, green and blue, as shown in Figure III.2.
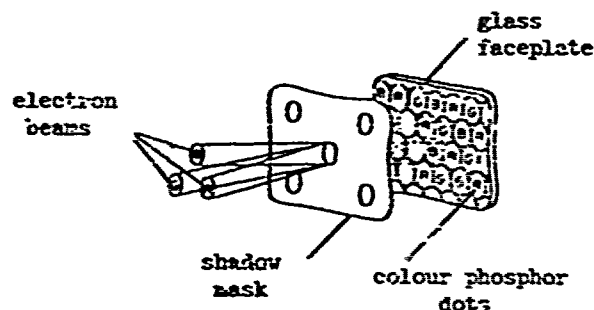
Figure III.2   The shadow mask colour CRT

Near the screen and parallel to it is a mask with a pattern of holes arranged such that each hole is aligned with a triangular group of three phosphor dots. Three electron guns, one for each colour are geometrically placed so as to illuminate only one phosphor dot each through any given aperture. Shown plotted in Figure III.3 are the chromaticities of the red, green and blue colour television phosphors recommended as primaries for the PAL system I [116] and NTSC systems [117]

The disadvantage of the system is the limited res-
olution attained. Variations of this technique have similar
properties, notably the *trinitron* tube which has vertical
strips of phosphor and a shadow mask. The *Lawrence tube*
also has vertical strips of the three phosphors but has a
single electron gun. Colour selection is made by directing
the beam through a wire grid close to the screen and apply-
ing a signal to the grid. However, none of these systems
exhibit sufficient resolution in the close viewing ATC
environment.
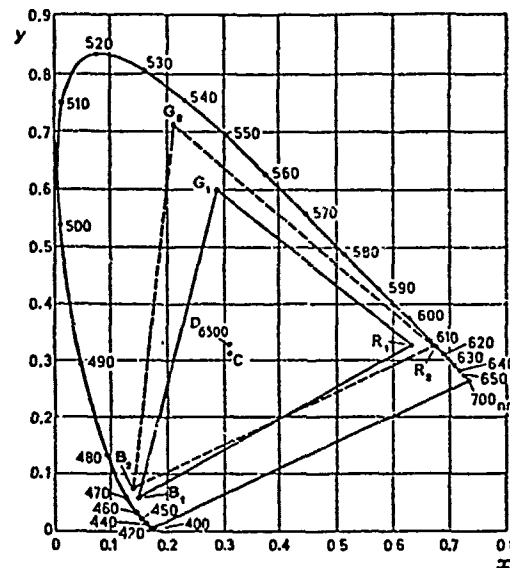
Figure III.3 The CIE chromaticity diagram of colour
             television primaries

The most likely colour display to be accepted for ATC
use in the *Penetron tube*. The operation of this device was
described in Chapter 2.4.1 and it is illustrated in
Figure III.4.
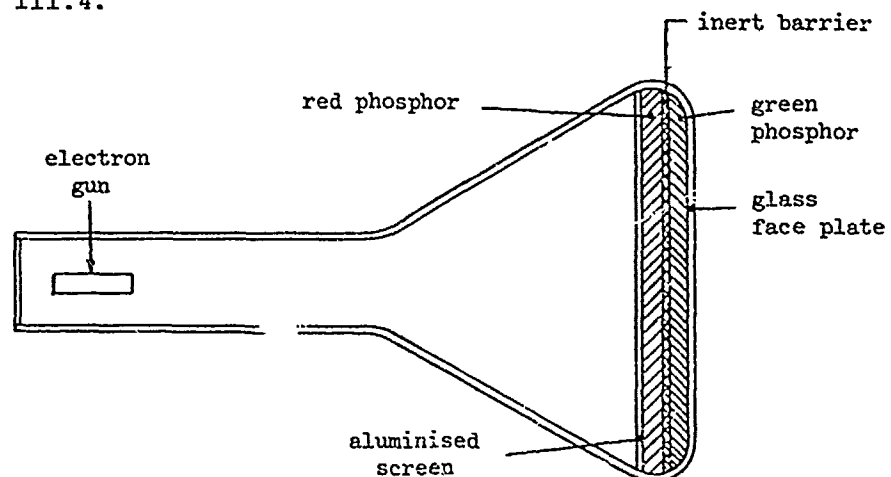
Figure III.4   The Penetron tube

The number of distinctive colours available is limited to
four or five, however in most coding applications more than
this number is undesirable from a human performance point
of view. The chromaticity locus of a typical tube is given
in Figure III.5.
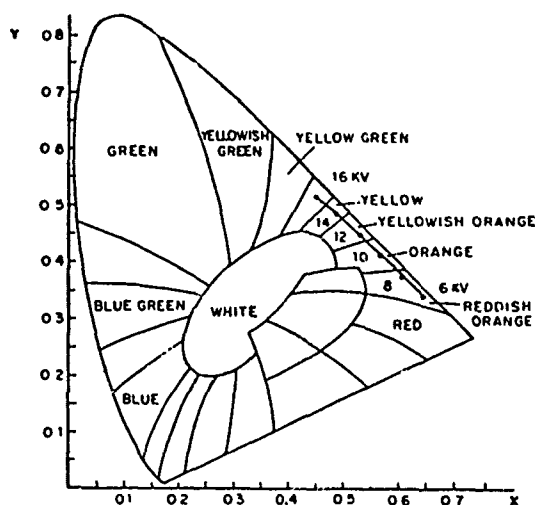
Figure III.5 Chromaticity diagram of a typical penetron tube

Data presentation on CRT displays often requires wide
bandwidth deflection systems to cope with large amounts of
data and consequently noise and jitter of the image can
become a problem. Special techniques have been developed
in order to get over this problem such as the charactron
tube described in Appendix II.2.2. Another technique
utilizes a multibeam CRT [118] to increase the information
bandwidth of the display.

III.2 THE GAS DISCHARGE (PLASMA) PANEL [30]

The gas discharge panel consists of a two dimensional
array of gas discharge which can be selectively established
by a cross-bar addressing system. In many designs the dis-
charges are confined in separate cells formed by an array
of small apertures in an insulating plate which is placed
between two electrode systems as illustrated in Figure III.6.
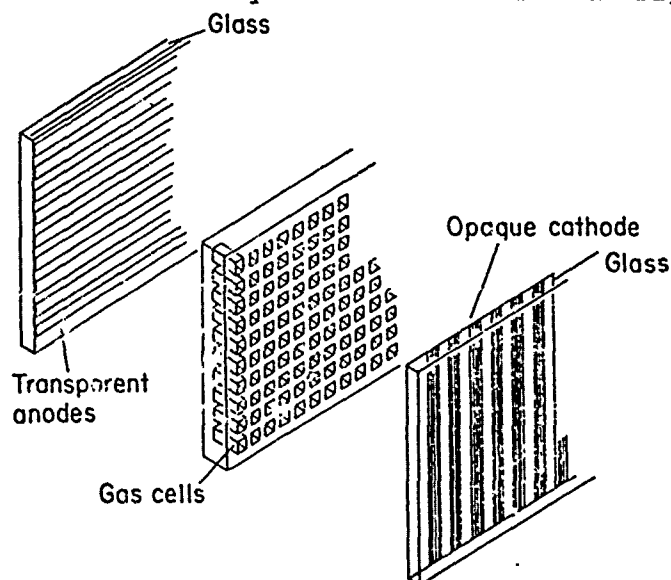
Figure III.6 Exploded view of a cross-bar discharge panel.

The three plates are sealed together enclosing a gas mixture, predominantly neon, at reduced pressure. Neon has a higher light output efficiency than other gases, of the order of 0.5 lumens/watt, which gives a clearly visible display in daylight at modest current densities. Although requiring a supply voltage greater than 100 volts, the threshold of the neon glow discharge are such that it may be switched on or off by voltages and currents compatible with solid state circuit technology.

The panel can be operated under a.c. conditions in which each set of electrodes act alternately as anodes and cathodes, or under d.c. conditions in which one set of electrodes acts permanently as cathodes and the others as anodes. In the a.c. operation the electrodes need not be in contact with the ionised gas, but may be isolated from it by an insulating layer.

The d.c. gas discharge [25] panel is usually biased at about 150V and half-select pulses (see Appendix I.5.1) are superimposed on both electrodes to ignite the cell. Memory can be obtained by providing a resistor in series with each cell,[28] and in this case brightness values up to 1000ftL. can be obtained because the cell is permanently on. *Self scanning panels* [27] have been developed using a technique which allows the transfer of glow discharge from cathode to cathode and an extension of this approach provides grey scale.[29]

The a.c. gas discharge panel has the advantage of inherent internal memory [24] which will be explained with reference to Figure III.7.

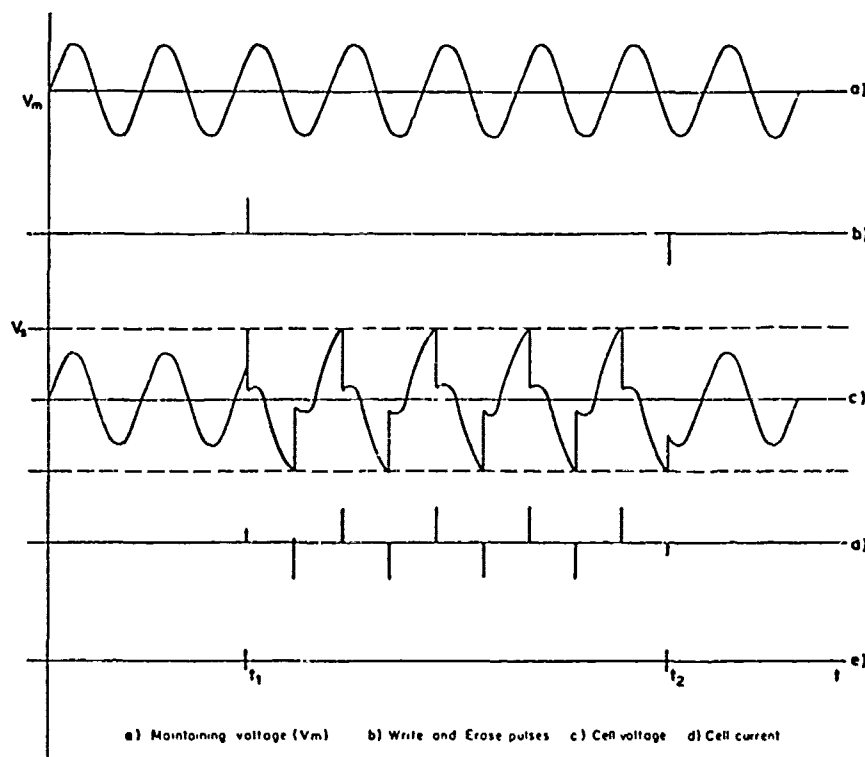a) Maintaining voltage (Vm)   b) Write and Erase pulses   c) Cell voltage   d) Cell current

Figure III.7   Voltage and current waveforms of an a.c. gas discharge cell.

A maintaining voltage, V_m, is applied to the electrodes (a) and by capacitive coupling a similar voltage exists across the cell but it is arranged that the cell voltage is below the striking voltage, V_s, as shown in (c). An equivalent circuit for the cell is shown in Figure III.8.
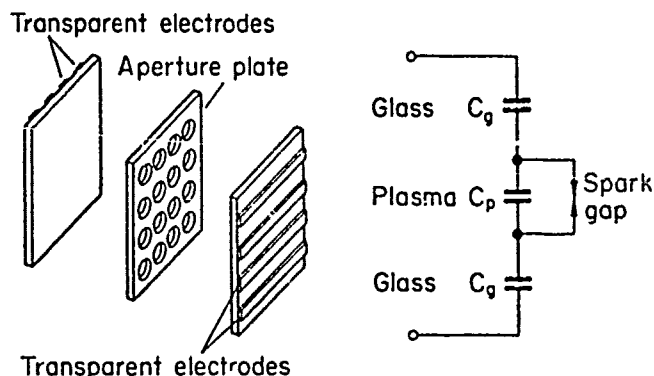
Figure III.8 **Exploded view of an a.c. gas discharge panel and equivalent circuit**

At time t_1 a positive pulse (b) is superimposed on the sustaining voltage taking cell voltage above V_s so that the cell fires and additional ions separate to create an additional wall charge across the cell which opposes the applied voltage and extinguishes the discharge. The residual wall charge is such that it will aid the voltage build-up in the next half cycle and take the cell voltage above V_s causing another discharge. At each discharge reversal of the wall charge takes place and the cell continues to fire every half cycle, (c) and (d). The discharge is erased by applying a negative pulse to the sustaining voltage at time t_2 such that it opposes reversal of the wall charge, reducing it to zero and thus extinguishing the cell. Typical characteristics are V_m of 200 to 250V at 50 to 250KHz and half switching pulses of 30-60V with brightness in the order of 50ftL although brightness is dependant on the maintaining voltage frequency.

Colour is possible by using xenon which emits ultra-violet radiation and stimulates phosphor deposits on the walls of the cells [23]. Alternatively the phosphor may be activated by low energy electrons.[22]

III.3 ELECTROLUMINESCENT DISPLAYS [33]

Junction electroluminescence [36] occurs in p-n devices where the recombination process is predominantly radiative and the semiconductor band gap exceeds 1.8eV in order that the radiation is visible as shown in Figure III.9.
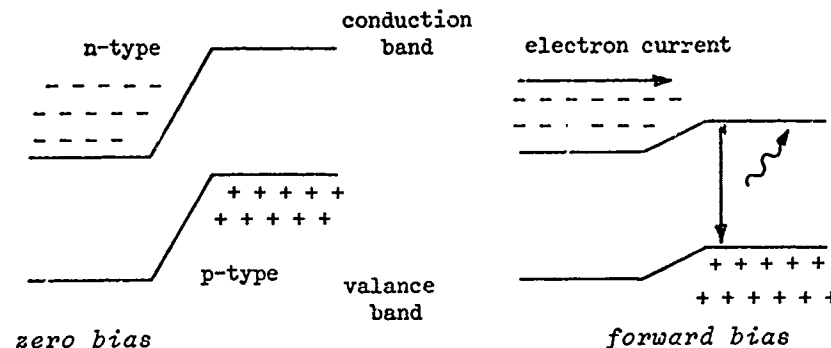
Figure III.9   Band structure of a p-n junction

The diffusion technique and associated planar technology are the most widely exploited and allow complex monolithic devices consisting of arrays of individual diodes to be made economically. The most common materials used to date are GaP, GaAsP and GaAlAs [36] and Figure III.10 shows the spectral emission of these and other materials. Although the efficiency of GaP emitting in the green region is not very high, this corresponds to the peak in eye sensitivity (also shown on Figure III.10) giving an overall luminous efficiency close to that of the red emitting compounds. A GaP diode has been produced such that its colour varies between red and green depending on the drive current.
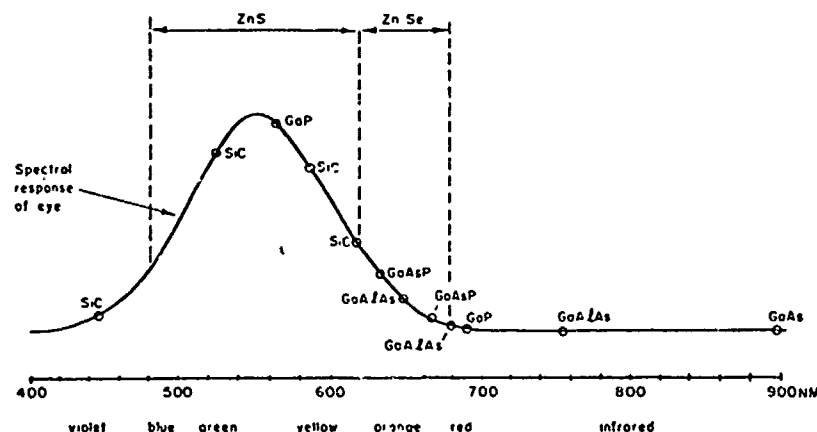
Figure III.10   Spectral emission of some EL materials

The efficiencies of the diodes are such that the current drivers are still required to interface them with most logic circuitry although the voltage requirements are directly compatible with TTL circuitry. Their high reliability is somewhat degraded if luminances higher than about 1000ftL are achieved by increasing drive current. The highest efficiency is achieved with red RaP and is in the order of 6-7%, but some materials have efficiencies of 0.1% or less. Switching times are in the order of nanoseconds and the devices exhibit a sharp threshold which is an advantage in matrix displays (Appendix I.5).

Matrix displays may be formed using two techniques:

1) multichip or

2) monolithic

The multichip array requires the bonding together of discrete elements whereas the monolithic array consists of p-n junctions diffused on a single substrate. Both techniques suffer from difficulties in producing large arrays, even a 100 x 100 array requires 10,000 diodes which must be laid down accurately and bonded or diffused. A 100% yield under such circumstances is beyond current technology.

Field effect electroluminescence devices are normally constructed by sandwiching the electroluminescent material which is suspended in resin, between two electrodes, one of which is transparent as illustrated in Figure III.11. A potential applied across this "capacitor" causes light emission and both a.c. and d.c. devices are possible. Colour is dependant on the material used and the activator, the most common phosphors being of the zinc-sulphide (ZnS) family.
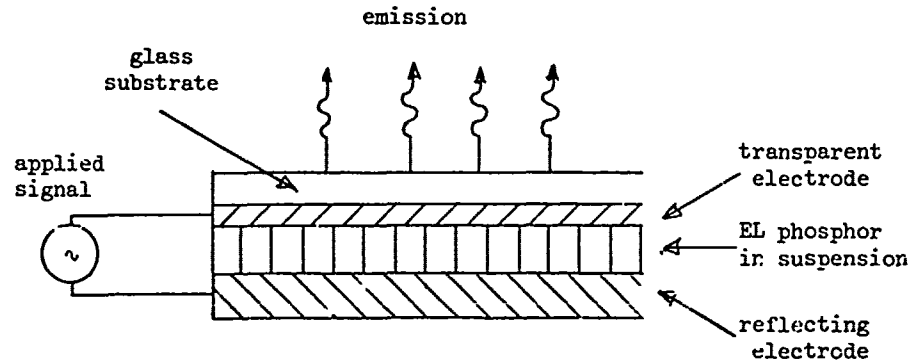
Figure III.11 A field effect electroluminescent device

This display thus far suffers from problems of low brightness, generally in the range of 5-50ftL, and poor reliability. Drive voltages in the order of 50-200 volts are required. The technique is particularly well suited, however, to large area displays of several hundred lines resolution. Present research is directed towards improving the life and brightness of these displays and has progressed to a point where they are quite competitive with LED devices.[35]

Almost the complete gamut of visible colours should be available from electroluminescent compounds in the future [34] so that they become a most attractive matrix display device. Table III.1 lists most of the compounds in which electroluminescence has been observed, those compounds underlined are of practical use. [33]

Table III.1 lists most of the materials in which electroluminescence has been observed and those which show promise in display applications have been underlined.

II-IV COMPOUNDS		III-V COMPOUNDS		OTHER MATERIALS	
ZnS	ZnSe	GaP	GaAs	SiC	Ge
CdS	CdSe	GaAsP	GaAlAs	Si	NaCl
ZnO	CdTe	GaInP	GaN	C (diamond)	AgCl
BeO	MgO	GaSb	InP	ZnFz	CaFz
CaS	SrS	InSb	InAs	Al_2O	Cu_2O
BaS	PhS	BN	InAsP	SnO_2	TiO_2
PbSc	PbTe	AIN	AIP	$BaTiO_3$	$SrTiO_3$
ZnTo				$CaTiO_3$	kNO_3
				$PbZnO_3$	$CaWo_4$
				$ZnSiO_4$	ice
				and other organic materials	

Table III.1 **Materials in which electroluminescence has been observed**

III.4 LIQUID CRYSTAL DISPLAYS [37]

A thin film of liquid crystal is held between transparent plates, the inside surfaces of which are coated with transparent electrode patterns so that voltages may be applied across areas of the film. These voltages produce electro-optic effects which modulate the incident light on the device. Liquid crystals are organic compounds having some of the properties of liquids but with an ordered crystalline structure.[38] Although many compounds possess the properties of liquid crystals only a few exist in this state at normal temperatures and the temperature range is usually limited. Liquid crystals may be classified into three classes according to their crystalline structure; *smectic*, *cholesteric*, and *nemetic*, and these are illustrated in Figure III.12. In each case the long, cigar shaped molecules are arranged in an orderly pattern under normal conditions.
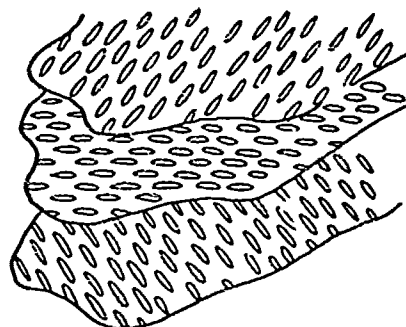
a) SMECTIC

b) CHOLESTERIC

c) NEMATIC

Figure III.12 **Crystalline structure of liquid crystal types**

Smectic molecules lie in parallel layers perpendicular to the plane of each layer and do not normally respond to electric fields. They are therefore of little use in display devices.

Cholesteric molecules are arranged in parallel layers with the molecules in each layer mutually parallel and in the plane of the layer. There is a constant angle of rotation of the axis direction from layer to layer. An interesting characteristic is that they change colour under the influence of a d.c. field, but despite this little effort has been devoted to their development as a display device.

Nematic materials [39] have the least orderly crystalline structure and in the passive state the molecules are aligned with their longitudinal axes mutually parallel. The electro-optic effects of nematic crystals exploited to produce display devices are

  1) dynamic scattering

  2) electrically controlled birefringence and

  3) twisted nematics.

Dynamic scattering in nematic compounds is caused by current induced disturbances. The electric dipole moment of nematic molecules does not lie along the molecular axis hence an electric field causes ion flow and a space charge build up. The consequent shear forces cause turbulence in the molecular arrangement and changes in refractive index, thus what is normally a transparent liquid will scatter light when a field is applied. The layer is usually 5-30 microns thick and the crystals may be either in a homeotropic (molecular axis normal to electrode) or homogeneous (molecular axis parallel to electrode) state.

There are several ways of exploiting the dynamic scattering effect and the three most common techniques are illustrated in Figure III.13.
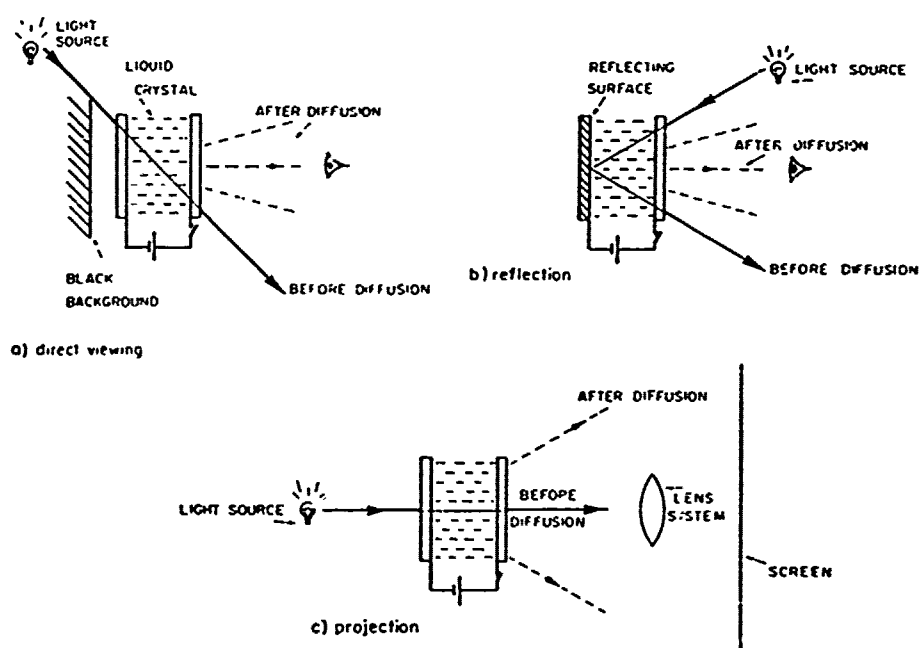
Figure III.13   Display techniques employing the dynamic
                scattering effect

If light is passed obliquely through the layer as in (a) the cell appears dark to the viewer until a field is applied and the light is scattered. The reflective technique is similar but the light source is on the same side of the cell as the viewer and the rear plate of the cell has a reflective coating (b). The scattering effect can also be used to construct a projection display as in (c).

The slow response of the device means that the pulse amplitude of a multiplexed display must be increased with reducing mark-space ratio. Also increasing drive voltage much above the threshold causes other cells to activate and degrades the display (Section I.5). Dual frequency address-ing is used as a solution to this problem [40]. Figure III.14 shows the relationship of peak switching voltage to duty cycle ratio.
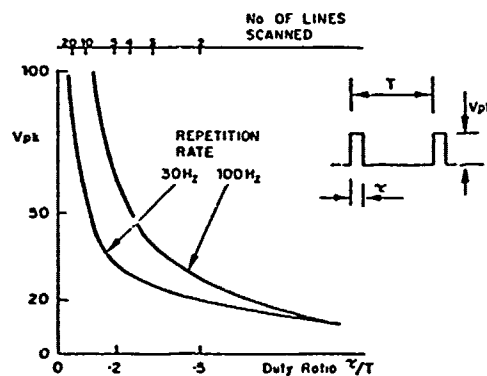
Figure III.14   Peak drive voltage as a function of duty cycle ratio

Electrically controlled birefringence (ECB) is a field effect and occurs when an electric field is applied to a hemeotrcpic liquid (molecules perpendicular to the elect-rodes). If light is passed through a polarizer, through the cell, then through a second polarizer set at 90° to the first, the device will appear dark when unactivated. Application of a field causes light to be transmitted, the colour of which is dependant on the applied voltage. Although ECB has advantages when used in matrix displays, manufacturing difficulties and narrow field of view at present retard its progress.

Twisted nematic devices are homogeneous liquid crystals but with the direction of the molecular axis rotated from one layer to the next. This has the effect of rotating the plane of polarization of plane polarized light. An applied field tends to straighten the helix arrangement of molecules and change the angle of rotation of the plane of polarization so that when placed between a pair of polarizers, the device exhibits high contrast and sharp threshold.

Typical characteristics of nematic liquid crystal display devices are given for comparison in Table III.2.

	Dynamic scattering	ECB	Twisted nematic
Effect	Current	Field	Field
Drive (volts)	10-40	4	2-4
Current ($\mu A/cm^2$)	10	1	1
τ_r (ms)	10-20	10	10
τ_d (ms)	100-200	100	100

Table III.2 **Typical characteristics of nematic liquid crystal devices**

III.5 PROJECTION DISPLAYS

Suitable projection techniques fall into three classes:

1) laser displays

2) CRT projection and

3) light valves.

Lasers have two properties which make them seem most suitable for large screen colour displays; their high brightness and optimal depth of colour. However, in spite of the fact that the laser is many orders of magnitude brighter than thermal light sources, the actual brightness of commercial laser systems has not reached the power level of about 1 watt/m^2 required for large screen displays. Other than holographic techniques for 3-D displays, laser displays fall into two categories; those in which the laser beam is used to write information on to optically sensitive material such as photographic film which is then used to modulate another light source, and those in which the laser light is projected directly on to the viewing screen.

Electro-optic deflection systems [41,42] have been developed and one of the most promising for application in random access displays is the *birefringent crystal* such as a calcite crystal preceded by an electro-optic polarization switch. Cascading n such devices gives 2n resolvable beam positions. The refractive index of a birefringent crystal depends on the plane of polarization of the light entering the crystal so the polarization switch is arranged to rotate the plane of polarization between two orthogonal axes. In one polarization state the beam will pass through the crystal undeflected, in the other it will be deflected through an angle. If the thicknesses of the crystals follow a geometric progression, then a linear distribution of beam positions is possible as shown in Figure III.15. The most common electro-optic switches are nitro-benzine liquid and potassium dihydrogen phosphate (KDP) crystals. Unfortunately both suffer from needing drive voltages in the order of kilovolts to achieve a 90° switch.
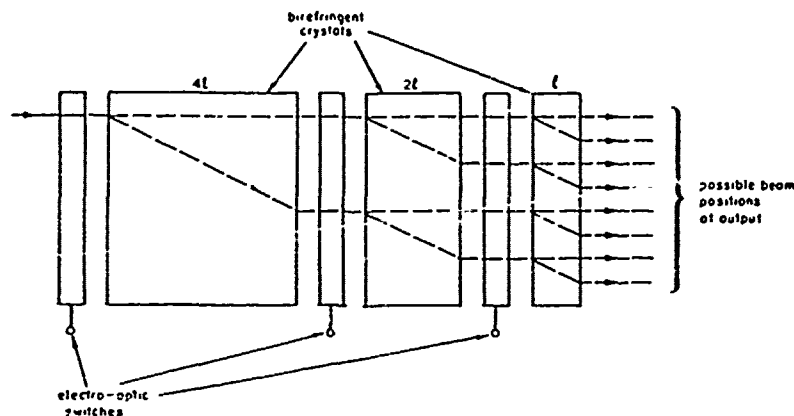
Figure III.15   A laser beam deflection system

Resolution in the order of 1000 lines is possible with such a system and the deflection time between any two positions is less than 1μs.

The laser can be used to write on photographic film or on photochromic materials,[43] which become opaque when subjected to light of a particular wavelength. The disadvantages are the slow response of photochromic materials and the fact that they usually require heat for erasure.

CRT projection displays generally involve the use of an external light source projected through the screen as the normal image is not bright enough in itself for direct projection. The potassium chloride screen of the skiatron tube becomes absorbent to green light when bombarded by electrons. Transparent phosphors exist which become opaque when subjected to ultra-violet light and when painted by an electron beam become transparent to green light. Back projection by a high intensity light source allows the image to be reproduced on a large screen.

The light valve relies on modulation of light by deformation of an elastic reflecting or transparent film, the deformation being produced by a surface electric charge deposited by a scanning electron beam. The original light valve was the Eidophor which is illustrated in Figure III.16 and it uses a transparent dielectric oil film on a concave reflecting disc to modulate light from a high intensity light source directed on to the film by a schlieren mirror system. Resolution is limited to around 1000 lines and colour is possible by rotating a disc made up of three primary colour sectors in front of the light source.
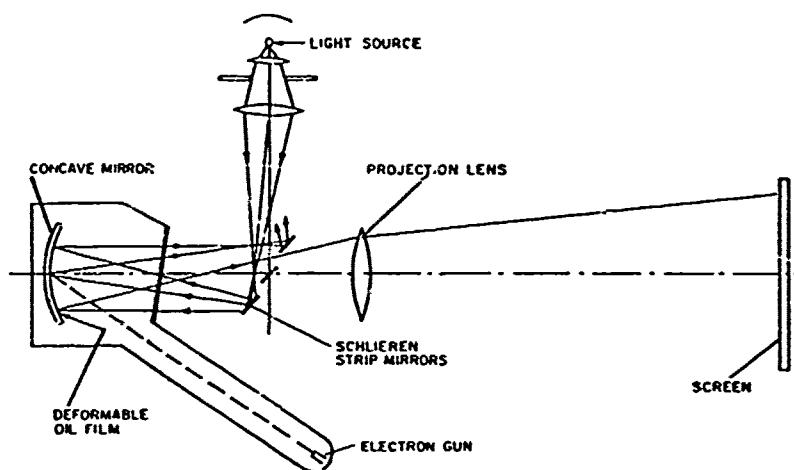
Figure III.16   The Eidophor projection display

A later improvement is the use of deformable plastic films to replace the oil and rotating disc.[44] Also separation of the deformable surface from the electron gun assembly reduces cathode contamination which is one cause of unreliability in the Eidophor display.

APPENDIX IV

VIDEO MAP GENERATORS

IV.1 THE FLYING SPOT SCANNER

An optically flat, high definition microspot cathode ray tube is used as a flying spot scanner, the light output of which is passed through a photographic plate. The light beam which has been modulated by the map inscribed on the photographic plate is focussed by a precision lens system on to a photomultiplier. The trace is triggered by the radar transmitter and then swept in synchronism with the antenna by either a fixed or rotating coil deflection system. Constant definition is achieved over the entire CRT face by dynamic focussing and shaping of the scan-current waveform minimises tangential deflection errors and improves linearity. The photographic plate must be prepared to very high standards of accuracy and master drawings are usually prepared from information on ICAO charts and drawn on a highly stable base material such as melinex. The master drawing is then photographed with an accurate reduction ratio to produce a photographic negative. The layout of a flying spot scanner video map generator is shown in Figure IV.1.
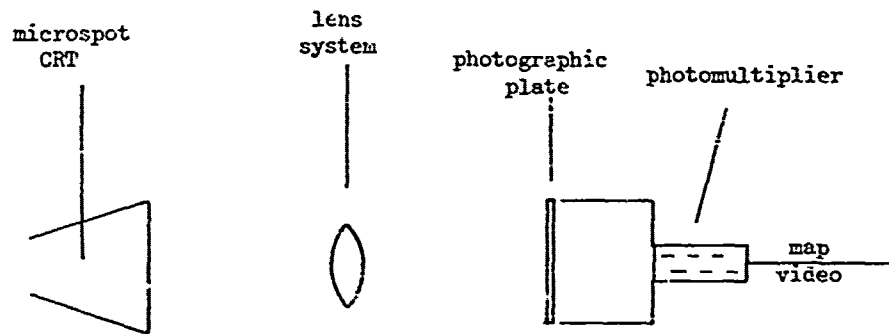
Figure IV.1 **A flying spot scanner video map generator**

Typical performance [119,120] figures are given in Table IV.1.

Map Range   10 - 400 NM

Accuracy:

  range   ± 0.5%

  bearing   ± 15 minutes of arc

Resolution   1/1000 of a radius

Stability:
  range drift ± 1%

  bearing drift ± 15 minutes of arc

Operating conditions

  temperature   - 10 to + 45°C

above performance t   ± 5°C

Dimensions
  Height   200 cm.
  Width   60 cm.
  Depth   70 cm.

Weight   300Kg.

Power consumption 0.5 kVA

  Cooling   forced air

Prices (October 1977)[58]

  basic unit with 4 slides   £30,000
  extra slides   £800 each

Table IV.1 <u>Typical flying spot scanner performance figures</u>

    There is a lower limit on the width of a radial map line
which will not be lost between successive sweeps. This is
dependant upon the angular spacing of the sweeps, the resolu-
tion of the scanner and varies with range. The minimum line
width in millimetres may be expressed as:

$$L = K. \frac{\text{Antenna RPM x Range}}{\text{radar PRF}} + C$$

where K and C are both dependant on the resolution of the
flying spot scanner. The actual artwork line width, G, is
equal to L multiplied by the reduction ratio used when
producing a slide from the artwork (typically 10:1). It is
normal to use line widths which may be resolved at maximum
range rather than vary the linewidth with range. Under
these circumstances a typical expression for line width
where the reduction ratio is 12:1 is given by:

$$G = \frac{\text{Antenna RPM x 5.23}}{\text{radar PRF}}$$

IV.2 GRAPHICS DISPLAY VECTOR GENERATOR

A display vector generator allows a constant intensity line to be drawn between any two points on the display and normally operates under the control of the display system computer which must provide it with the following information:

1) Start point co-ordinates

2) Finish point co-ordinates

3) Length

4) Vector rate components

5) Intensity level

6) Start drawing sequence.

All the information defining a radar video map is stored along with changing target information in the display computer memory and is then drawn on the screen as a series of line segments.

Typical performance [121] figures for a graphics display vector generator used in a radar system are given in Table IV.2.

Display characteristics

Screen diameter	50 cm.
Refresh rate	55 Hz
Max. beam width	.75 mm
Deflection bandwidth	3.5 MHz

Vector Generator

Writing rate	0.45 mm/μs
position resolution	.006 mm (8192 x 8192 element grid).

Table IV.2 Typical vector generator characteristics

IV.3 THE REAR PORT PROJECTOR

The *rear port* is a flat glass window parallel to the screen mounted in the cone of a CRT. Photographed information is projected through the window on to the screen where the phosphor acts as both an optical projection screen and an electronic screen so that the observer is presented with a combined image. The projector may contain a number of frames which present alternative combinations of information remotely selected. The geometry of a rear port CRT is shown in Figure IV.2.
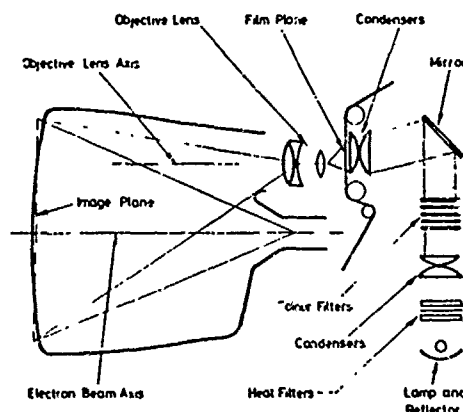
Figure IV.2   The rear port projection system

Registration is complicated by the fact that an electronically generated grid pattern on a curved tube faceplate will suffer from pin-cushion distortion whereas an optically projected grid will suffer barrel distortion as illustrated in Figure IV.3.

electronic grid distortion   optical grid distortion
(pincushion)   (barrel)
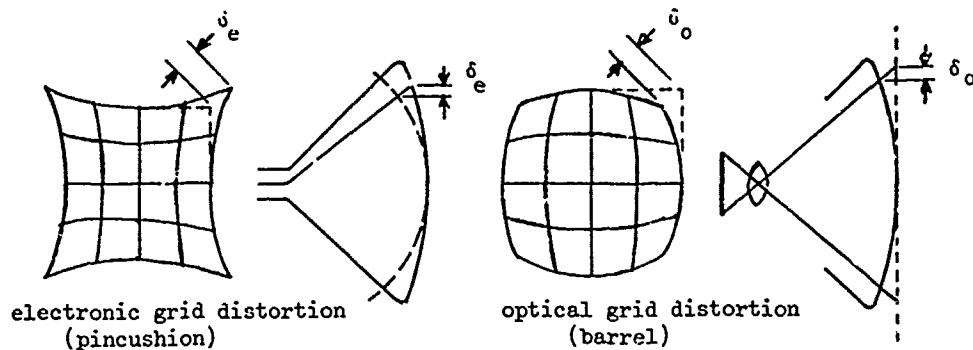
Figure IV.3 Rear port projection distortions

This problem may be overcome by predistorting either the electronic or optical data or both. Typical performance figures [18] for a rear port projection CRT display are given in Table IV.3.

Registration	1%
Resolution	0.5 mm
Repositioning	0.2%
Power consumption	100 watts

Table IV.3   Typical rear port projector characteristics

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FLAT PANEL DISPLAY TECHNOLOGY OVERVIEW

(Extracted from 1979 Tri-Service Airborne Flat Panel Display Technology Report)

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INTRODUCTION

Today's, and more importantly tomorrow's, military aircraft and associated displays must be extremely flexible to cope with a wide variety of weapons and weapon delivery options, active and passive countermeasures, enemy weaponry, and complex pilotage problems. Need for increased capabilities has driven all three services to investigate new technology to replace the existing limited devices such as the cathode ray tube (CRT), incandescent readouts, and electromechanical displays.

CRTs presently being employed in military displays, while satisfying the need for flexibility, are bulky devices requiring high operating voltages, high power, and a great deal of maintenance and do not lend themselves well to being driven by today's solid-state technology.

Flat-panel technology, however, offers considerable savings in the physical area of panel space, behind-the-panel depth, weight, power, cooling, and life cycle costs, while offering vastly improved reliability, flexibility and ease of retrofitting. Basically there are three display media which are presently receiving the most attention and appear to be the most promising. These are (1) electroluminescence (EL), (2) light emitting diode (LED), and (3) liquid crystal (LC), all of which are described in succeeding paragraphs. There are other technologies that also appear promising but that have not advanced in development to the point where they are receiving serious consideration for aircraft use or that have serious limitations, some of which may be eliminated in time. These include plasma, electrochromic, electrophoretic, ferroelectric, magnetic particle, and microchannel plate display technologies. In order to exploit flat-panel display media, development of suitable addressing techniques is required. Three representative methods of addressing display media (silicon, thin-film transistor (TFT) and crossed electrodes) will be discussed.

Display Media

ELECTROLUMINESENCE (EL). Electroluminescence (EL) enjoyed a surge of interest in the late 1950's and early 1960's which quickly subsided when seemingly insurmountable lifetime problems coupled with poor contrast were encountered. Fortunately, some researchers continued to work with this technology and significant progress has been made in the intervening years. The maintenance (half-life of brightness at a given drive level) of ac-driven powder EL phosphors was increased to the point where useful lifetimes were assured, solving the earlier EL lifetime problem. Subsequently, evaporation of thin film layered structures including a layer of manganese-activated sinc sulfide produced devices that maintain a constant brightness with time, and lifetimes of 20,000 hours have been reported.

In these devices, the phosphor layer lies between two insulating layers (usually yttrium oxide), and this structure lies between two electrodes, the front one of which is transparent. Electrically, the device resembles a capacitor and must be driven by an ac voltage to produce the alternating electric field within the phosphor film that excites the electroluminescence. An advantage of this approach is that the resulting light-emitting structure is transparent, allowing high contrast display devices to be produced by placing a black layer behind the light-emitting film. The effect of this increased contrast is such that the display on the device, when viewed directly, is legible in direct sunlight illumination of 100,000 Lux (10,000 fc) with outputs less than 68 cd/m^2 (20fL). Routinely achieved luminous efficiencies for such films have been 0.6 lumens/watt. Recently, however, reproducible efficiencies of 4.0 lumens/watt have been achieved in 5" x 3.5" panels. At the 0.6 lumen/watt efficiency, a 6" x 3", 30 lines per inch display will dissipate 800 mw with all of its 256 characters turned on and legible in direct sunlight. The discrimination ratio (sharpness of the brightness/voltage curve) is high enough to allow multiplexing of fairly large x-y addressed panels; a fact that has resulted in successful demonstration of the graphic and video capabilities of this technology. Furthermore, response time is

fast enough for nonsmear TV operation and is acceptable under the full military temperature range.

LIGHT EMITTING DIODE (LED). Light emitting diode technology is based on an electroluminescent phenomenon referred to as carrier injection electroluminescence. In the presence of an electric field of proper polarity, loosely bound electrons on the n-doped side of a pn junction drift (i.e., are injected) across the diode junction region where, upon entering the p-doped region as minority carriers, they combine either by direct or indirect band gap transitions with majority carrier holes producing both light and heat. Primary success has been achieved in forming efficient light-emitting junctions in single crystalline solid-state compounds from group III and group V elements in the periodic table, including: (GaP) (green, yellow, orange and red emission), (GaAsP) (orange and red emission), and (GaInP) (yellow emission). Other less efficient group III-V, II-VI, and IV-IV compound LEDs remain in a less developed state due to a combined lack of commercial interest and government support. GaN falls in this category, but is noteworthy because it has the potential for producing a full-color display. As a technology, LEDs are continuing to evolve at a rapid pace. The LED has a demonstrated record of reliability, long life, ruggedness, compatibility with integrated circuit drivers and is adaptable to many display applications. Power consumption can be expected to decrease appreciably for most types of LEDs. In matrix-address LED displays luminance uniformities adequate for video imagery have already been achieved. Additional development would be required, however, to improve LED efficiency to the point where seven grey shades would be readily visible in direct sunlight. Further effort is required to produce the same legibility at the maximum demonstrated resolution of 128 pixels/inch as is achieved for the 64 pixels/inch resolution presently being used in LED arrays suitable for alphanumeric and vector-graphics applications. There are near-term applications for the individual modules as flexible-form-factor spin-offs of the modular vector-graphic displays now under development. In the near term, LEDs are expected to be most heavily applied in the aircraft discrete-data-readout display applications that are presently dominated by incandescent-filament-based display devices, and in flexible information format message displays such as radar homing and warning panels, weapons status panels, and warning, caution, and advisory annunciator panels. Aviation Red and Yellow LEDs that appear to be adequate to satisfy these applications already exist. Aviation Green LEDs having adequate efficiency are not yet available, although several promising candidates have been demonstrated.

LIQUID CRYSTAL (LC). Liquid crystal display devices are passive, using electro-optic materials to modulate ambient light by means of scattering, birefringence, polarization, absorption, or combinations of optical effects. Dynamic scattering and twisted nematic are the two most commonly used modes of operation. Dye-based, phase-change phenomena appear to show great promise for future displays. LC displays may operate as reflective devices returning a portion of the ambient light to the viewer's eye or they may be fabricated from transparent materials and used in a transmissive mode. An integral light source may be used with either mode of operation. Applications range from digital watches to large screen projection systems with full-color images. LC displays are generally credited with the following advantages:

° Low-Voltage Operation - Typically from 2 to 20 volts depending on the application, making them compatible with any form of semiconductor drive circuitry.

° Low Power Operation - Typically from 0.05 to 0.5 microwatts/pixel. Most system requirements, which may include a light source and/or heating, still result in low-power operation for most applications.

° Good Viewability Under Direct Sunlight Conditions - Due to the passive nature of the display, contrast is relatively independent of ambient and 8 to 10 shades of grey is achievable in the reflective mode.

° High Reliability and Long Life - Too early for authoritative conclusions, but tests to date and basic failure mechanism analysis indicate operating life times of 10,000 hours or more.

State-of-the-art LCs have the following limitations:

° Provisions for external lighting must be considered due to passive nature of display.

° Existing LC materials cannot meet the full military operating temperature range without temperature control. Typically, this can be accomplished by heating. For a 5" x 5" display, representative power values would be 5 watts sustaining after a 100-watt, 90-second warmup from a cold soak.

Commercial developments have concentrated on numeric displays. Increasingly, LCs are displacing LEDs in the watch and calculator markets because of their lower power dissipation and lower cost. DoD efforts have concentrated on the development of multipurpose displays which can display alphanumerics, graphics and sensor images. The state-of-the-art in these developments is represented by 3.5" x 3.5", 100-pixel/inch display for a total of 122,500 pixels which can display TV images. Present response times are in the millisecond range.

PLASMA. There are two basic types of plasma displays: those that operate on ac voltage, and those that operate on dc voltage.

The ac devices typically utilize a neon argon gas mixture enclosed between dielectric-

coated conductors in order to produce an orange glow when proper voltages are applied to the conductors. The Owens-Illinois Digivue consists of two glass plates with gold electrodes on each plate. The plates are arranged such that the electrodes on one plate are orthogonal to those on the other. A dielectric coating is placed over the electrodes and the two plates are separated by small glass rods or beads prior to sealing and filling with gas. Display resolution of 2.0-2.4 lines/mm (50-60 lines/inch) for presentation of graphics has been achieved with this type of panel. Luminance is typically 70-170 cd/m^2 (20-50 fL). The fact that the panels can be made transparent also increases their versatility. Static information such as a map background may be placed behind the panel or projected on the rear surface. The ac panel is bistable and therefore does not require a refresh memory as do CRTs. Presently, ac displays are being used in commercial computer terminals and in some major military ground applications.

The dc gas version differs from the ac version in that the electrodes are not separated from the gas mixture by a dielectric layer, but are in direct contact with it. A discharge at one point in a dc gas discharge panel makes it very easy to initiate another discharge at an immediately adjacent point. Self-scanning panels utilize this effect by incorporating a multi-phase clock producing a sequence of voltages to propagate a scan-glow across the display. The inherent memory of the ac panel is lost, but full grey scale capability is gained. Panels capable of presenting about 500 characters with about ..2 lines/mm (30 lines/inch) resolution are readily available, and many companies have produced experimental single and multi-color TV displays with this technique. The refresh requirements dictate that about 200 columns of information are a maximum limit on size. Luminance is generally about 170 cd/m^2 (50 fL), but some panels have exhibited well over 340 cd/m^2 (100 fL). Typical effective luminous efficiency of 0.1 lumens/watt has been achieved, resulting in a power dissipation of approximately 4 watts when all of the characters of a 30 line/inch, 256 character display are on. These characters are legible in relatively high ambient illumination. At present, the commercial panels emit the standard neon orange glow, however, experimental devices incorporating a variety of phosphors have exhibited other colors. In practice, the dc panels have been widely used only in the alphanumeric mode in applications requiring a few hundred characters, such as a bank teller's terminal. The military is employing the Burrough's dc panel in developmental models of the Army Digital Message Device which is a microprocessor controlled, hand-held, battery-operated display carried by a forward observer. Existing technology does not allow utilization at either the low end or high end of ambient light conditions. In addition, plasma displays are not directly IC addressable.

ELECTROCHROMIC. Electrochromic technology capitalizes on selective absorption in certain organic and inorganic materials and thereby utilizes ambient light reflected back to the observers' eyes. An electric field is applied to a film of the electrochromic material which is usually placed between a transparent conductor and an aqueous electrolyte solution. Typically, tungsten oxide (WO$_3$) is used as the electrochromic material, resulting in a blue or white display. Some other interesting color effects have been obtained with lutetium diphthalocyanine constructed in both opaque and translucent cell configurations. Ranges of color, from rose through a somewhat neutral shade of grey, to green-blue-green, deep blue, and violet have been obtained by controlling the applied voltages. Electrochromics satisfy military operating temperature requirements and exhibit memory capability; however, material problems relative to stability and efficient excitation of the electrochromic material have to date prevented the utilization of this technology.

ELECTROPHORETIC. Electrophoretic technology utilizes reflectivity based on the transport of charged pigment particles in a colloidal suspension. The colloidal suspension is a dyed nonaqueous suspending fluid having pigment particles of a contrasting color dispersed in it. This fluid is then sandwiched between two transparent electrode surfaces of glass plates. Depending on the polarity of the electrodes, the pigment particles are driven to either the front or rear surface of the sandwich structure. The observer, therefore, sees either the pigment or the suspending fluid which are different in color, resulting in the observed display phenomena. Because of the reflective nature of the device, displays are very attractive, looking like ink on paper. Material problems still exist with this technology; however, it is expected to be a very viable candidate for display use when these problems are solved.

FERROELECTRIC (FE). Ferroelectric (FE) technology incorporates transmissive devices which are birefringent and change the velocity of propagation of light (along two axes of vibration) by application of an electric field. Therefore, white light, consisting of a multiplicity of wave lengths within the visible spectrum, will experience a continuously variable phase shift across the spectrum when passed through a polarizer, the FE material, and another polarizer as the FE material is energized by an electric field. The use of FE ceramic material has several disadvantages. When used in the birefringent mode, two polarizers are required which reduce light transmission to about 25%. The material is temperature sensitive so that it exhibits a Curie temperature where the birefringence falls to a very low level. Voltage levels for activation are not IC compatible since they are in the 300 to 500 vdc region. The material exhibits a large capacitance and has hysteresis characteristics so that all voltages must be approached from the same direction. The material also requires transverse excitation which means either depositing interdigitized electrodes or cross-slotting the material itself.

MICROCHANNEL PLATE (MCP). A microchannel plate is a plate made up of conductive glass tubings which act as electron multiplier channels through secondary emission. These plates are approximately 0.1 mm thick, typically with a tube diameter of 12 microns (0.47 mils) with 15 micron (0.59 mils) center-to-center spacing, and variable gains up to

10^5. Microchannel plate technology has been pursued in relation to image intensifiers and other display applications for some time. There is work underway on an experimental display device consisting of a cathode, microchannel plate, and a phosphor screen. The cathode and MCP are structured as an array, with the cathode striped vertically and the MCP striped horizontally. When one stripe on the cathode and one line on the MCP are addressed simultaneously, one pixel located at their intersection would be activated. With a video modulated light source illuminating the entire cathode, synchronous, sequential array scanning would result in a display of the video information on the phosphor screen.

MAGNETIC PARTICLES. The magnetic-particles display is a flat-panel, matrix-addressable display device. Freely rotating, tiny, spherical permanent magnets, each of which is half dark and half light in color, form the image of the display. The amount of ambient light reflected by the particles is a function of the rotation or orientation of the particles which is controlled by an applied magnetic field. The magnetic field emanates from a nearby array of electromagnets that function as a nonvolatile memory. Sites in the memory can be selectively magnetized by currents through conductors imbedded in the display.

"QUASI" CRTs. Current efforts to redesign and shorten CRTs for display purposes dictate that this technology be considered in any discussion of flat panel displays. Two of these technologies are discussed below. The results obtained to date preclude the evaluation of these technologies at this time.

"Flatscreen" operates by extracting electrons from a gas discharge and accelerating them to high energy to excite conventional CRT phosphors. Scanning is accomplished by an X-Y matrix. Depth dimensions using this approach have been reported as low as three inches.

"Area Cathode" approach replaces the point source cathode of the conventional CRT with an area source cathode consisting of an array of closely spaced filament wires. A multi-layer control and switching stack is inserted between the cathode and phosphor screen. The depth of this mechanization has been reported to be two inches.

Display Addressing

THIN FILM TRANSISTOR ARRAYS (TFT). Significant advantages can be obtained using flat panel displays by placing active control elements at the location of each picture element on the panel. TFT switching devices can be deposited over those large areas necessary for many display addressing applications. The gain of these devices provides the necessary discrimination for X-Y addressing, minimization of cross-talk, and maximizes brightness by providing an essentially 100% duty cycle for an "on" element. Since the TFTs are used only as switches and can switch analog as well as digital input signals, grey scale operation is an inherent capability of this approach. The voltage levels and output capabilities of these devices make them compatible with a wide range of display technologies including electroluminescence, liquid crystal, and electrophoretics. Single crystal technology is not easily compatible with large area display devices but, at the same time, such displays do not require the device qualities for which single crystal technology is noted. Thin film transistors nicely fill this gap.

The producibility of 6" x 3", 222 by 77 line (37 x 26 lines/inch) TFT addressing arrays has recently been established on a pilot line facility, and samples of this display using powder phosphor are available now and have been delivered for incorporation into experimental models of the AN/PSG-2 (Digital Message Device). Ongoing efforts are directed toward combining these TFT arrays with the high contrast, thin film phosphor structure and integration scanning circuitry to the periphery of the array using compatible TFT circuitry. The resulting device will combine the advantages of small size and weight, low power consumption, excellent legibility under all conditions, operation under the full military temperature range, and a minimum of external connections. The first of these fully integrated displays is expected to be available in 1979. In the meantime, designs for handheld terminals and aircraft instrumentation displays using this technology are being initiated.

INTEGRAL SILICON DRIVE. The highly refined silicon processing techniques of the semiconductor industry can be used to produce matrix arrays which provide an integral, active element for control of each picture element. This technique, at present, has been confined to liquid crystal displays.

This approach makes use of the technology and production equipment that have been developed for high volume LSI production operations. High density configurations are possible, and the resulting switch devices are of high quality and uniformity. (Up to 58 pixels/inch over an area of approximately 0.25" by 0.25" had been demonstrated.) At present, the size of the display module is limited by commercial processing equipment and silicon wafer technology. The 3.5" silicon wafers now used have produced display modules which are .175" square (an array of 175 x 175 pixels). Larger display surfaces must be carefully assembled from the basic modules, and module size will be paced by the commercial processing lines. Arrays have also been successfully fabricated using Silicon on Sapphire (SOS) that simplifies the processing steps, increases the voltage breakdown threshold and, because the sapphire is transparent, produces transparent drive arrays. Further development in this area is hindered by the lagging interest of commercial houses in SOS technology for other applications. Charge coupled device (CCD) technology has produced sensor arrays of matrix elements which are scanned to read out the image using

bucket brigades of CCD shift registers. It has been suggested that a matrix display could be fabricated in an analogous manner, with the image shifted in. CCD may offer distinct advantages in simplification of the addressing problem.

CROSSED ELECTRODE MATRIX. The approach of utilizing a simple set of crossed electrodes for driving a matrix display is used with a variety of display materials including LED, LC, plasma panels, and EL films. The applicability of this approach as an addressing technique depends on the extent of the nonlinearity of the display material involved. This approach is being coupled with a thin film electroluminescent phosphor to form a passively driven matrix display—a display without an active element at each picture element site. The success achieved depends on the extremely nonlinear brightness vs. drive voltage characteristics of the electroluminescent film layer which minimizes crosstalk from activated picture elements. Typically, with line at a time address, half the required voltage would appear on one row electrode, and half would appear on the column electrodes with the appropriate pulse width modulation to obtain the desired brightness level for those picture elements being activated. This approach has recently been demonstrated over a small area at electrode densities of 500/inch with crosstalk contrast values on the order of 70:1. The approach has also been used to demonstrate a 180 x 240 element panel (at lower element densities) with a black background layer for real-time TV which is legible in bright room ambient.

THE ELECTRO-OPTICAL DISPLAY / VISUAL SYSTEM INTERFACE: HUMAN FACTORS CONSIDERATIONS

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SUMMARY

Display systems are currently developed by a cyclical two-stage process. An equipment is developed, and there is then a period in which its suitability for use by an operator is assessed. The results of the evaluation determine the modifications which will be introduced into the next cycle of the process. This paper considers the possibility of adopting a design strategy which initially assesses operator performance and then uses the result of this assessment to determine what equipment development would best meet the requirements of the operator. As the subject under consideration is visual display systems, the text considers only the visual aspects of human performance and relates these attributes to display parameters.

1. INTRODUCTION

The rapid advances that have recently occurred in technology, particularly in the microelectronics industry, have created an environment in which the systems designer has at his disposal a vast number of design options which only a few years ago were not available. These developments have given him the capability to construct systems which are more complex than any previously envisaged. This situation has come about by two means; firstly, we are rapidly reaching a situation where the designer is able to request the introduction of novel techniques, knowing that such requests can often be met, given sufficient time and financial investment; secondly, many modern systems are now based on relatively old, well-proven hardware which permits flexibility by means of software options. The designer increasingly finds himself in a position of having to select what he considers to be the optimum combination of hardware and software to produce a viable system. This selection process is proving more and more difficult, and frequently represents the critical activity in the design phase of a system.

Whereas in the past almost every information source that could be made available was rapidly incorporated into the cockpit, and the problems encountered related to the selection of the optimum display device, position and format, there are now so many sources and derivatives of these sources that the problem frequently becomes one of selecting the correct derivative to display to the pilot. There can be little doubt that the military pilot's information requirement has been increased by the need to carry out precision navigation and weapon delivery tasks at low altitudes whilst flying at high speed in conditions of reduced visibility. However, because the piloting task has increased in complexity it is essential that the information presented to the pilot should assist in simplifying the task and not make it even more difficult.

The pilot may be considered as a discontinuous, sequential operator[1] of limited capacity, with the ability to process and act on information at a rate which is extremely slow compared with the speed obtainable with microelectronics. Although microelectronics may be superior to the human for carrying out relatively mundane calculations, the pilot is made irreplaceable by his ability to access information at random in his memory and make decisions based on novel combinations of information sources. If we assume that these particular human qualities necessitate the retention of a pilot as part of an overall system, we must carefully consider how this will affect the critical decisions made by the system designer.

It would appear that whilst the pilot is able to provide the flexibility within the system, which microelectronics and associated software alone cannot offer, this flexibility is achieved at the cost of seriously reducing the speed of operation of other parts of the system. One could argue that when the electronic systems are operating correctly the pilot becomes the limiting element. If this is so, it should be the role of the system designer to appreciate the nature and extent of the pilot's limitations and design his system to minimise their effect, at the same time making best use of the pilot's superior performance in other activities.

Traditionally the system designer has paid careful attention to ensuring that the major sub-components of a system are correctly matched, so that the overall transfer characteristic of the hardware is optimal. During the design and prototype assembly phases the research staff reduce the number of switching and software options they are prepared to make available to the pilot. Frequently this latter process is carried out in a very unsystematic manner, based on the intuition of the designer. Eventually the complete system may be assessed in a flight trial, when a very limited number of pilots may provide subjective assessments of the system. Even if trials are mounted in which objective data are gathered, all too often the number of data points gathered is insufficient to analyse the complex interaction of parameters that occurs. Consequently, this makes it impossible to assess the system accurately. In addition, the limited time available in the air and the problems associated with an equipment refit make it difficult, if not impossible, to introduce and evaluate modifications. The introduction of programmable digital avionic systems should in theory improve the ability to introduce modifications but one cannot help but wonder whether, in the future, software changes are going to be any less difficult to implement than hardware changes have been in the past.

The traditional approach outlined above is an "evolutionary approach" in which there is no ideal specification towards which the designer's activities are directed. The approach is one in which the specification is based upon a refinement of the specification used to produce the last generation of equipment, and relies upon past experience to make modifications to what are considered to be the most important parameters. One cannot deny that this approach has proved successful in the development of many systems, but there are also examples where a badly conceived system has been continuously refined to realise an only partially adequate final result, and in these cases a total redesign should have been undertaken. There is little to be gained from intellectually brilliant developments of a concept which is fundamentally wrong.

What then are the alternatives? Should we design by exclusion rather than by inclusion, removing all the parameter combinations that obviously will not work for one reason or another and retaining all the potentially viable combinations for further evaluation? Obviously, the answer to this alternative must be "no", as we would create impossibly large numbers of combinations which we could not hope to handle in any systematic analysis. Perhaps the answer lies in the phrases "ideal specification" mentioned above. Should we not ask ourselves whether such an entity could exist when first addressing the design problem?

The designer all too often forgets that he is attempting to produce a system for information _transfer_ and not just information _display_. It is the transfer process which is all important and involves not only the sensor/display system but the human operator (pilot) as well. The system designer should therefore consider the operator as an element within the system, and should incorporate human performance characteristics into his calculations when attempting to assess the relative potentials of alternative systems. It may be that we would approach the "ideal specification" if we were to design systems that were matched to human performance characteristics; after all, a human will eventually operate the system. If we allow ourselves to be convinced that such an approach may have at least some possible benefits over the evolutionary approach, we must now consider how to proceed.

Having hopefully stimulated the reader to consider at least the possibility that data from experimental psychology studies may have some relevance to system design problems, it is not the intention of the authors to present masses of numerical information which may cause such confusion that the fundamental concepts cannot be grasped. It would appear to be much more profitable to make the reader aware of the types of information available in specific reference sources and outline the relevance of the data to particular design problems.

2. THE OBJECTIVE MEASUREMENT OF HUMAN PERFORMANCE

Innumerable measurement techniques have been devised to quantify specific aspects of human performance. Many of the techniques realise data in a form which makes them unsuitable for use by the system designer. It becomes impossible to derive an "ideal specification" because all too often the units adopted are incompatible with those of the parameters manipulated in the rest of the display system. Display performance may be described typically in terms of a modulation transfer function (MTF). In the 1960's it was realised that the MTF approach could also be applied to the human visual system. The opportunity at last appeared to exist to enable certain attributes of the visual system to be represented in the system calculations. Although considerable developments have occurred since these early beginnings, proving the relevance of the measure to display design, the fundamental difficulty of applying MTF techniques has not changed significantly. There are at least two separate aspects of the visual system which must be considered[2]: the spatial transfer characteristics and the temporal characteristics. One must now consider how these descriptive parameters relate to the essential operations that occur in the perception of visual information.

The visual perceptual process may be conveniently subdivided into two major subprocesses: the peripheral reception process which occurs at the eye, and the integration and decision making process which occurs centrally within the brain. In the first of these subprocesses may be included the fundamental activity of signal detection, whilst the second subprocess contains more complex activities such as signal processing, signal correlation, pattern recognition, decision making and response

control. All these   l components of the perceptual process possess non-linear
and discontinuous p   ies which make it extremely difficult to utilise an MTF
approach to describe the entire mechanism quantitatively. It is possible, however, to
generate data which at least partially describe the simpler aspects of vision, such as
the detection of radiant energy in the eye, the transmission of semi-processed
information to the brain and certain aspects of central processing. As many of these
simpler operations provide the essential information on which the more complex
processes operate, great potential benefits are to be gained by ensuring that the
properties of such operations are fully appreciated and that equipments utilise their
performance to the full. The data are insufficient to describe the pattern recognition
process, although several attempts have been made to model this extremely complex
activity[3]. The authors concede that although such models have certain credibility,
they represent a very specialised application of the MTF approach and consequently fall
outside the terms of reference of this paper.

In the sections which follow, the discussion describes the procedures adopted to
realise MTF data for the simpler perceptual operations before considering them in terms
of their relation to display image parameters. Where appropriate, the interactions that
may occur and the compromises that may have to be made in system design are indicated.
Throughout the text emphasis is placed on the visual conditions that must exist for the
efficient transfer of unambiguous information across the electro-optical display /
visual system interface.

3. DISPLAY SYSTEM PARAMETERS AND SPATIAL MODULATION TRANSFER

The spatial modulation transfer function of the visual system may be plotted by a
technique devised by Campbell[4] which requires subjects to respond to a sine-wave grating
of known visual angle. By presenting a sine-wave grating of known spatial frequency
(calculated as cycles per degree of visual angle) on a cathode ray tube and increasing
the signal luminance modulation until the grating becomes visible, the threshold of
detection for the known spatial frequency can be obtained. By repeating the procedure
over a range of discrete spatial frequencies, a curve of spatial frequency by screen
luminance modulation can be plotted; this is the so called spatial MTF curve of the
visual system. Unlike the MTF curve for an electronic system, which precisely describes
the system, the MTF curve produced by the above technique only describes the visual
system's characteristics under the conditions present when the data were obtained.
However, by adapting the procedure, spatial MTF curves may be obtained which relate more
precisely to the design problem under investigation. For example, simply by changing
the spectral emission of the cathode ray tube the effect of wavelength and bandwidth on
the transfer characteristic can be evaluated[5], or by changing the orientation of the
grating relative to the visual vertical the orientation specificity of the visual system
may be revealed[5].

The fact that a family of MTF curves may be generated indicates the complexity of
the interface under consideration. It is important to realise the relevance of
individual display parameters, but even more important to understand the way in which
parameters interact; the correct selection of the most important parameter interactions
for optimisation is essential if the optimum display / visual system interface is to be
produced.

Having outlined the magnitude of the problem with which the designer is faced, let
us now consider how spatial MTF data for the visual system may facilitate the
selection of particular display parameters for further investigation. Perhaps the
easiest way of presenting the relevant information to the reader in a manageable form
would be to consider each component of the electro-optical display / visual system in
turn, and to show how each element relates to frequency and modulation data independ-
ently. This, however, is only partially possible as the frequency and modulation
components of a visual stimulus cannot be considered to be orthogonal. In the sections
which follow an attempt has been made to discuss these two aspects of the stimulus
independently, and where interactions occur the relative importance of each of the two
stimulus dimensions is indicated.

3.1 Display Surround

The panel and instruments surrounding an electro-optical display reflect at least
some of the incident ambient illumination, and this reflected light is often perceived
in peripheral vision whilst fixation is directed to the display. The presence of this
peripheral stimulation not only causes changes in the adaptation state of the eye, but
also affects perception in the central portion of the eye retina owing to the
significant spatial interactions that occur within the system[7]. The presence of
peripheral stimulation by the light reflected from the panel thus has the effect of
changing the eye's spatial MTF, with the nett result that the ability to perceive low
signal modulations and high spatial frequencies within the display image under fixation
is reduced.

The peripheral stimulation may take several forms, ranging from discrete glare
sources, which may be due to highlight reflections from instruments, to even surround
luminance caused by general reflection from the panel or uniform emissions from adjacent
displays. It is more usual for a combination of these two extremes to exist when a
complex panel is under observation. Fortunately the effects of glare sources on vision
within the central retina are additive[8] and this enables the effects of a number of
sources causing simultaneous peripheral stimulation to be calculated. The effect on the

eye's spatial MTF of each source is proportional to the illumination produced at the eye by the source, and is approximately inversely proportional to the square of the angular separation from the line of sight to the image under fixation. Because of this additivity an even surround may be considered as an infinite number of small glare sources in order to perform the necessary calculations.

Glare effects have been quantified experimentally by determining the luminance an even surround must possess in order to have the same effect as the glare source on the eye's spatial MTF. By this means it has been possible to explore systematically the effect on the eye's MTF of peripheral stimulation caused by spurious reflections. The majority of results are in agreement that the ability to detect both low signal modulations and high spatial frequencies within the display image is optimal when the surround luminance to display background luminance ratio is unity[9][10][11]. Suprisingly perhaps, as this ratio is reduced below unity, i.e. the surround is darkened, the display signal modulations must be increased to maintain operator performance, but the increment required is only very gradual and over a limited range. When the luminance ratio is increased above unity, i.e. the surround becomes brighter, display image modulations must be increased rapidly and over a much larger range. The change in the eye's ability to detect contrast within the display image is proportional to the increase in the surround luminance that has occurred and follows the following relationship[11]:

$$C' = C_{ref} \left[0.9815 + \frac{0.0185 LS}{LB} \right]$$

where: C' = threshold contrast for a given ratio $\frac{LS}{LB} > 1$

C_{ref} = threshold contrast when $\frac{LS}{LB} = 1$

LS = surround luminance

LB = display background luminance

From the above it may be concluded that the optimum perception of display inform-ation is achieved when the luminance induced by the presence of ambient illumination on adjacent panel and instruments is equivalent to the background luminance of the display. Obviously any formulation which includes a term for display background luminance can only be applied to a situation in which alphanumeric or symbolic information is presented against a blank background. Difficulties arise when such formulations are applied to displays which are required to present a sensor derived pictorial image of the outside world on a raster or matrix format. Here no uniform background exists and the problem becomes one of deciding whether it would be beneficial to have increased asymmetric modulation from the adaptation level of the eye (i.e. the display background of the symbology case) or to have increased modulation symmetrical around the adaptation level. That is, should the black or the mid-grey level of the imaging display be equivalent to the display background term used in the above formula? This is a question which within the limits of out knowledge remains unresolved and is currently under investigation.

Only luminance contrast has been considered above but more recently the introduction of colour displays offers the possibility of using colour contrast. A second type of adaptation must now be considered, which also affects the MTF of the eye. The presence of a coloured surround may induce a change in the colour adaptation of the eye which can dramatically alter the apparent colour of the displayed information. For example, a red surround can cause a yellow symbol to appear green. To alleviate this problem it is recommended that, wherever possible, display surrounds should be black, grey or white to ensure colour balance in the peripheral retina and thus reduce the possibility of differential colour adaptation occurring. The introduction of multiple colour display installations may present specific difficulties, as several large areas of dissimilar colour may be present simultaneously in peripheral vision, causing indeterminate changes in the adaptation which may result in the incorrect interpretation of colour coded information. Further studies are urgently required to investigate these effects more fully.

3.2 Display Visual-Field Size

The visual angle subtended by the display at the eye depends not only upon the absolute size of the display but also upon the real or apparent viewing distance. When the display image is viewed indirectly, via an optical pathway, the optical components themselves rarely limit the performance of the system significantly. Perhaps the major exception to this statement is when a fibre-optic bundle is introduced into the pathway. For all but the latter type of optical element, the transmission of spatial frequencies up to the maximum of 60 cycles per degree of visual angle resolvable by the eye can comfortably be met by the optical components. The attenuation of display image modulations which may occur within the optics significantly reduces visual performance only at the highest spatial frequencies. In indirectly viewed systems the design of the exit pupil often limits operator performance more than the simple transmission losses. The relationship between the total field of view and the instantaneous field of view is particularly important, especially in binocularly viewed systems such as the conventional head-up display, where portions of the field may be viewed monocularly

whilst other portions are viewed binocularly. Precise image alignment must be achieved in this and similar systems to ensure that the optimum convergence of the two eyes results, in order to reduce eye strain and false depth cues to a minimum[12].

In the design of both directly and indirectly viewed systems it is essential that the display image plane falls within the accommodative range of the eye (approximately 0 to 6 dioptres) if high spatial frequencies are to be resolved[13]. Within this range maximum performance can be obtained over prolonged periods of observation by positioning the display image at the resting position of accommodation (mean 1.7 dioptre)[14][15], thus ensuring that maximum spatial resolution is achieved with minimum muscular fatigue. When the image is positioned near or outside the limits of the operator's accommodative range, high spatial frequencies can no longer be resolved and performance rapidly deteriorates. It must also be remembered that it is not easy to specify absolute design limits, since the range over which accommodation is possible differs significantly from operator to operator. In addition, the range available is seriously reduced with increasing age[13], and this may represent a primary consideration in defining the final position of the display image, particularly in civil and surveillance aircraft where the operators may be more mature.

Assuming the above considerations have been used to define the position of the image plane of the display system, simple calculations may be performed using display image size and subtended visual angle to obtain the magnitude of the smallest displayed area that will remain within the spatial bandwidth of the visual system[16]. It is pointless to develop flat panel or cathode ray tube displays which are capable of displaying information far beyond the bandwidth of the visual system, since the information will simply not be perceived. The calculation outlined above provides a method for defining approximately the minimum picture point size that is required at the display surface if the entire bandwidth of the operator's visual system is to be utilised. Regrettably, even if such high spatial frequencies were to be displayed, the signal modulation required to enable them to be perceived would be extremely high and would probably be beyond the capabilities of most display devices. Because of this serious limitation, the calculation may be more appropriately used to determine what spatial frequencies the operator will be able to resolve within the limitations of the display technology. If the operator's task is one of identifying small targets, which may be represented as high spatial frequencies, the result of this calculation may influence the choice or field of view of the sensor adopted to provide the image signals. The same calculation also allows one to predict whether the raster structure of a CRT or the matrix format of a flat panel display will be clearly and perhaps disturbingly visible at the eye.

In addition to determining the detail visible within the display image, the angle subtended at the eye by the image determines the area over which visual search must be performed. The majority of visual information is assimilated via the central fovea of the retina, which is directed to areas of high or relevant information content, but additional information of low spatial frequency content may be assimilated by the peripheral retina. The extent to which peripheral display information is available is primarily determined by the visual angle subtended by the display image. Data in the literature describing the ability to perceive image modulations in peripheral vision appear initially to contradict each other, but the inconsistencies may be resolved when the adaptation of the eye is taken into account. Plots produced during scotopic adaptation show that the ability to detect luminance modulations improves with increasing eccentricity from the fovea[17] until an asymptote is reached at 5 degrees. In photopic adaptation, however, increased luminance modulations are required with increasing eccentricity[18][19]. As would be expected from the above, spatial frequency resolution is also retinal position dependent. The highest spatial frequencies are best detected at the centre of the fovea, with a measurable loss in spatial resolution occurring at as little as 5 minutes of arc of eccentricity. Beyond this point spatial resolution falls off extremely rapidly with increasing offset, until at approximately 20 degrees little further decrement in performance occurs[20][21].

One may conclude from the above findings that, since the perception of high spatial frequencies may only be achieved by the central retina, a display which subtends a large visual angle may not significantly increase the ability of the operator to assimilate information about a stationary image. On the contrary, the large area over which visual search must occur to allow the fovea to extract relevant information may substantially reduce performance. However, the ability of the peripheral retina to detect movement information in a display image is an important factor determining the final selection of display visual field size (see Section 4.2).

3.3 Monocular, Biocular or Binocular Viewing

Monocular systems have the potential advantages of being smaller and cheaper than binocularly viewed displays. Their small size may also permit them to be brought close to the eye to produce a much larger visual-field than is possible with a panel mounted display. Although initially the use of monocular displays appears attractive there are several operational features which must be evaluated before selecting this option.

Monocular displays frequently have a very limited exit pupil which requires the operator to position his eye extremely close to the display optics. For a display mounted in the panel this has the obvious disadvantage of requiring the pilot to make large physical movements which are time consuming and seriously disrupt his search activities across areas remote from the display. In the airborne environment where flying activity is primary, this is the major factor which restricts the use of

monocular displays in single seat aircraft. In dual seat aircraft the operating environment is less restricted and the second crew member may have sufficient time at his disposal to make a head-down monocular display a viable proposition. However, there can be no doubt that the presence of information in the non-display eye which is either totally uncorrelated or only partially correlated with the information in the display eye causes decrement in visual performance. Under certain circumstances fusion may occur across the two eyes, or the phenomenon known as binocular rivalry may occur. Rivalry is outside the terms of reference of this paper and the reader is directed to more extensive discussions of the subject[22][23]. Suffice it to say that this phenomenon dramatically affects the ability of the operator to process displayed information and ultimately may become the limiting element in certain monocular display systems such as the helmet-mounted display.

When the display is viewed with two eyes either biocularly or binocularly the operator frequently experiences increased comfort. There is no one factor which can account for this benefit, but the ability of the visual system to integrate the highly but not totally correlated information from the two retinae may reduce the effort involved in processing the signal within the brain. The summation of the two images which occurs is not total[23], but the overall effect of this binocular interaction is to improve the signal to noise ratio within the system, increasing the statistical probability of detecting signal modulations[24][25]. The nett result of viewing the display image binocularly is that the ability to perceive limiting contrast is improved, as is the ability to resolve high spatial frequencies[26].

For a single, directly viewed display image, the above effects are beneficial; however, for display systems such as night vision goggles, where two images may be present or a single image may be viewed biocularly, the mechanical alignment limitations of the display device may seriously erode the benefits to be gained from two-eye viewing. The visual system is relatively intolerant to vertical[27] and rotational[28] alignment errors which may cause convergence difficulties[29], double imaging[12] and subsequent loss in visual resolution. Unequal magnifications also make binocular image fusion difficult[30] and binocular rivalry may occur. The necessary degree of image correlation usually falls within the capabilities of most optical systems and care in the design and alignment processes associated with production can usually obviate all these difficulties and allow the operator to reap the benefits to be gained from binocular viewing.

3.4 Display Luminance

It is convenient to divide the discussion on display luminance effects into two sections. Firstly, since the MTF of the visual system is affected by the adaptation state of the eye, it is important to consider the average state of adaptation, which may be related to the average luminance of the display image and to the effects of surround luminance. Secondly, consideration must be given to the extent of signal modulations around the average luminance and to the spatial distributions of these modulations.

The average luminance of the display and its surround will determine whether the eye is operating under conditions of scotopic, mesopic or photopic adaptation. Over the range of luminances represented by these adaptation states, the pupil of the eye changes its diameter considerably[31], and this affects the ability of the retina to resolve high spatial frequency data[32]. At low luminance levels, when retinal illumination is low and scotopic adaptation exists, the ability to resolve high spatial frequencies is poor[33]. At moderate luminances, the ability to resolve detail increases rapidly, until a maximum value is reached when the pupil reaches its minimum size[34].

When scotopic adaptation conditions prevail, high signal modulations are required to make low and medium spatial frequencies visible in the image, and high spatial frequencies will not be perceived. In the mesopic range, the necessary signal modulations are of smaller magnitude and relatively high spatial frequencies will be visible. In the photopic range, signal modulation may be reduced still further and the highest spatial frequencies become visible[35]. Within the photopic range, a relatively constant relationship may be established between the absolute luminance of an area of the display image and the increase in luminance that must exist in an adjacent region in order that two separate grey shades may be visible. This is expressed in the Weber-Fechner Fraction (Luminance increment/Absolute luminance = Constant)[34]. The value of the constant is generally taken as 2% and using this figure it is possible to predict, using an iterative procedure, the number of perceptible grey shades that can be displayed. The complex spatial interactions that occur in the retina when areas of inequivalent luminance are juxtaposed allow this low 2% figure to be achieved[36], but in the absence of juxtaposition a contrast of approximately 7% is required to ensure perceptibility. This increase in contrast seriously reduces the number of grey shades which can be perceived in a display of limited dynamic range. A host of unusual interactions may be observed, affecting apparent image quality and raising doubts as to the validity of the use of the term "grey scale"[36][37]. All of the above effects are important in determining the ability of pilots to detect targets in display images.

Display luminance alone is insufficient to describe the conditions under which the display is used. The ambient illumination incident upon the display and its surround has a considerable effect on the pilot's ability to detect signal modulations. Light reflected from the display surface adds to the light emitted by the display and causes the mean luminance level to increase whilst at the same time reducing the effective signal modulation. To counter this effect a number of alternatives are available.

If the display has sufficient dynamic range, the luminance and modulation levels may be increased, but although this may appear to be the simplest solution, it is far from the best, since it may seriously reduce the life of the display. Also, the eye may be driven into saturation by increased display luminance, so that the pupil can contract no further and the limit of the ability to resolve high spatial frequencies is reached. A further adverse effect is that veiling glare within the eye may reduce retinal illumination modulation to a significant extent.

The most successful method for reducing the adverse effects of high ambient illumination is to use filters on the surface of the display. Simple neutral density filters can increase signal modulation by attenuating the display emission only once whilst attenuating the ambient illumination twice[39]. Polarising filters may achieve a similar improvement in signal modulation, but a far greater improvement can be achieved by the use of narrow bandwidth display emissions with matched absorption filters[40][41]. Although the peak luminance to the eye is considerably attenuated by the filter, the signal modulation is much improved and the display luminance can frequently be reduced without loss of information.

Display visibility in high ambient illumination conditions can also be enhanced by the use of directional filters, in which a structure of louvres or cells is arranged to prevent ambient light falling on the surface of the display except from the direction which is effectively masked by the pilot's head. The effectiveness of filters of this type is inversely proportional to the acceptance angle of the structure used and this makes them more suitable for aircraft with single-seat cockpits, in which the range of angles from which displays are viewed is very limited, than for transport aircraft in which cross-cockpit viewing of displays for monitoring purposes is required.

3.5 Display Colour

Because of technological limitations, airborne electronic displays have until recently been single-coloured (monochromatic). One of the major difficulties has always been to produce a display with sufficient luminance to compete with ambient illumination. The luminous efficiency $(V\lambda)$ of the retina is not equal for all wavelengths, and also varies with the state of adaptation[42]. In scotopic adaptation, at a wavelength of 507 nm minimum radiant energy is required to achieve a given subjective brightness, whilst rapidly increasing amounts of energy are required to maintain this brightness for changes in wavelength in either direction. In photopic adaptation, minimum radiant energy is required at 555 nm and more energy at other wavelengths. Since displays are used predominantly in conditions in which the eye operates photopically, many green displays have been developed. However, the current availability of more rugged phosphors for CRT's, capable of high radiant energy at different wavelengths, and of light emitting diodes operating at a variety of wavelengths, makes it possible to use alternative display colours. The operator factors which should be used in the selection of display colours now assume a greater importance than the technological factors.

Although in scotopic adaptation larger signal modulations are required at long wavelengths to enable high spatial frequencies to be observed[43][44], these levels are usually within the range of the display. At photopic levels, wavelength effects become insignificant in determining modulation levels required[43], and one must search for other criteria on which to base the choice of colour. There are various factors which influence this choice. The accommodative mechanism of the eye appears to be most strongly activated by yellow light and less affected by emissions of other wavelengths[45]. Since chromatic aberration occurs in the eye, because it is unable to refract all wavelengths equally, short wavelengths will be focussed in front of the retina when the eye is accommodated to primarily yellow light and long wavelengths will be focussed effectively behind the retina. The result of this phenomenon is to cause the eye to be myopic to short wavelengths and thus to yield poor acuity, whereas long wavelengths may be accommodated, though possibly at the expense of considerable eye fatigue. This is particularly true if the emissions are extremely saturated due to their narrow bandwidth. It could be argued, therefore, that short wavelengths should always be avoided and long wavelengths should be used sparingly. On the other hand, the increased visual saturation that can be achieved at the extremes of the visible spectrum[32][46] offers the opportunity to use colour contrast instead of luminance contrast to compete with ambient illumination[47]. On balance, it appears that the benefits to be gained by using colour contrast may be outweighed by the accommodative difficulties which may be experienced, and intermediate wavelengths filtered by contrast enhancing devices are to be recommended for all conditions except where scotopic adaptation is essential[48].

When multiple colours are employed on the same display surface, care must be taken to balance the radiant energy of each emission to take into account the effect of variation in luminous efficiency described above. A single balance equation is probably inadequate to maintain equivalent perceptible colour separation at all luminances, as the apparent hue of a given wavelength changes with luminance[49]. The accommodative effects already described are also very relevant when multiple colours are displayed simultaneously. Because of the inability to focus all wavelengths equivalently at any instant in time, the lens of the eye must be continually adjusted to bring into focus the information required[50]. When one wavelength is in focus, high spatial frequencies at that wavelength can be resolved, but the frequencies resolvable at other wavelengths are seriously reduced. This means that in a complex multi-colour display, only the detail at one particular wavelength may be resolved at any instant, a change in eye focus being required to see detail at other wavelengths. This refocussing may lead to

considerable eye fatigue, and may also present to the brain a distance cue which is inappropriate since it results from a two-dimensional image. The result is that the display, particularly when presenting symbology, may have an apparent three-dimensional quality, with some elements appearing to float in front of the display surface. One possible way of overcoming this effect is to desaturate the colours to facilitate refraction at the lens of the eye, but this seriously reduces the possibility of using bandpass filters to enhance image contrast.

An additional consideration is the sensitivity of the peripheral retina to different wavelengths of light[51]. The peripheral retina is able to detect red and blue emissions much more readily than green, but the response time to red peripheral stimuli is considerably greater than that for either blue or green. Few data are available describing the spatial frequencies which can be resolved peripherally at each wavelength. The trade-offs between luminous sensitivity and speed of response must be carefully assessed to meet any particular display requirements.

Even when care is taken to balance different wavelengths to maintain equivalent colour separation, and information is carefully positioned to make best use of peripheral vision, colour adaptation effects can negate all this careful planning. If the retina is adapted to a specific wavelength, the apparent hue of a stimulus may shift by the equivalent of 15 nm[52] towards the adaptation wavelength. This can cause difficulties in colour coding, since a code can appear to move into the next category. The effect is not limited to the situation where fixation changes from one display to another; unequal distribution of information in a relatively large display image may result in the generation of the effect. Spatial interactions resulting in simultaneous colour contrast can have similar, disturbing effects[53].

3.6 Visor/Spectacle Transmission

This element of the display system is often forgotten in the design phase simply because, like the operator, it is spatially separate from the integrated electronics comprising the display system. Visors designed solely to protect the pilot in the event of bird strikes, or ejection, may have a transmission efficiency greater than 80%, but attenuating visors are frequently only 15% efficient. The three main features to be considered in spectacles and visors are their attenuating properties, their wavelength specificity and the amount of dispersion that occurs in the material from which they are constructed.

The effects of attenuating average luminance levels and signal modulations have been pointed out in the section on display luminance. In addition to these, it should be remembered that the attenuation of ambient illumination that will occur when visors or spectacles are in use will result in a change of the adaptation state of the eye, and will affect modulation and spatial frequency sensitivity. If wavelength specificity is a feature of the optical material, this may prove beneficial in enhancing the apparent contrast of the outside world, or, if appropriately matched to the display emissions, that of the display[54]. In an environment where multiple wavelengths are present, care should be taken not to attenuate vital coloured information seriously.

Even when new, the optical materials which comprise the visor or spectacles often disperse light and produce veiling glare which further reduces the effective modulation of the display. When, with use, scratches and finger marks appear on the optical surface, these cause further dispersion, particularly in high ambient illuminations, and cause a dramatic loss in apparent signal modulation.

3.7 Raster or Cursively Written Display

Although these two types of display have strikingly different image formats, calculations based on display image characteristics show that only in one area are the differences major. If display image modulation were unlimited, the maximum spatial frequency resolvable at the eye would be the resultant of the relationship between tube spot size and viewing distance. Eventually the spot size becomes the limiting parameter and the minimum size achievable limits the horizontal resolution of both types of display. For the cursive display, vertical resolution is again limited by the spot size but the raster display may have either similar or inferior resolution, dependent upon the line standard adopted. Difficulties arise when symbology is to be written if the line standard used is considerably below the resolution limit of the tube. Whereas the cursive system has the ability to write smooth, continuous symbols, the raster system has to write discontinuously at spatial frequencies which frequently allow the discontinuities to be perceived, unless specialised signal processing is performed.

In typical installations, in an attempt to remove the disturbing influence of perceptible raster structure, the visual angle subtended by each raster line is brought close to the spatial frequency limits of the eye. As a result of using high spatial frequencies, the image modulation required is increased and this may become the limiting factor when the display is required to compete against incident illumination. In the raster mode, when writing symbology alone, the maximum luminances achievable are considerably (by a factor of 10 to 20) below those obtainable from a similar tube using cursive writing, owing to the requirement to spend time writing the entire raster structure. This enhanced performance obtainable by the cursive system makes it particularly suitable for use in conditions when the adaptation state of the eye is such that high luminances are required.

If symbology alone is required, the cursive system has much to recommend it; however, there is an increasing requirement for an overlay of symbology on sensor-derived imagery. Only the raster system is able to offer the flexibility that is necessary to meet this requirement, but the penalties paid are reduced luminance and discontinuous symbology.

The relative advantages and disadvantages of using the two alternative methods of address on colour tubes are related to the tube construction. Limited data only are available discussing this topic and further evaluations are required before the merits of each tube/address combination can be accurately assessed.

4. DISPLAY SYSTEM PARAMETERS AND TEMPORAL MODULATION TRANSFER

The temporal modulation transfer function of the visual system may be plotted by one of several widely differing techniques[32], but the one which has produced the most extensively used data is that devised by Kelly[55]. The procedure requires subjects to observe and respond to a luminance source which is modulated in luminance intensity sinusoidally with respect to time at frequencies between 2 and 75 Hz. Their task is to determine whether the source, modulated at a particular frequency, appears to be continuous or flickering when compared with a continuous luminance surround. By repeating the process over a wide range of frequencies, luminance modulation may be plotted against the temporal frequency necessary for fusion (the critical flicker frequency - CFF) to produce the so called temporal MTF of the visual system. As for visual spatial MTF data, the curve produced by the above technique only describes the visual system's characteristics under the conditions present when the data were obtained. Again, by adapting the technique, curves can be obtained which relate more precisely to the design problem under investigation.

The magnitude of the problem with which the designer is faced is considerably less than that experienced when utilising spatial MTF data, as the manifestations of the temporal characteristics of the visual system have less effect on overall system performance. The electro-optical display / visual system elements which must be considered are similar to, but not identical with, those presented for spatial MTF.

4.1 Display Surround

The mode of action of ambient illumination incident upon the surround, and the means by which it affects the adaptation level of the eye, have been discussed in Section 3.1. For temporal modulation detection the luminance adaptation of the eye appears to have considerably less effect than is the case for spatial modulation detection. The luminance of the surround has little influence on the frequency necessary to achieve fusion except at the limits of spatial frequency resolution[56]. However, the area of the constant luminance surround does affect performance, presumably as a result of the spatial interactions that occur within the retina. The CFF is found to increase linearly with the logarithm of the surround area[57].

The ability of the visual system to detect flicker at frequencies as great as 80 Hz at high average luminance levels, gives rise to doubts as to the advisability of incorporating raster displays using domestic frame rate standards into large installations. Only if the operational scenario is one in which the display is to be operated at modest luminance levels, in reduced ambient illumination, can the relatively low frame rates employed in present military systems be used without the introduction of peripherally perceived flicker from non-fixated displays. This limitation will be particularly relevant in the future to both military and civil cockpit installations, where ambient illumination may be high and several display images may simultaneously be present, all emitting high luminances. In both of these environments, the narrow bandwidth filters used for image contrast enhancement (discussed in Section 3.4) may be beneficial, not only by improving the legibility of the display under fixation, but also by reducing the peak luminances of the temporal modulations present in peripherally perceived displays, thereby reducing their apparent flicker.

The presence of such transient responses in peripheral vision has frequency specific effects. Frequencies below 3 Hz act as good alerting signals, directing the operator's attention away from the display being fixated[58]. Care must obviously be taken to ensure that any signals within this frequency range are not unintentionally present. Frequencies in the range 4 to 7 Hz cause tolerable discomfort, but modulations within the 8 to 15 Hz band cause confusion, with an accompanying loss of operator performance and in some sensitive operators even loss of consciousness. One cannot overstress the importance of avoiding such frequencies. Beyond 15 Hz and below 30 Hz luminance modulations are found to act as distractions and prove annoying but less so than the lower frequencies. Dependent upon the luminance levels prevailing, not until between 30 and 80 Hz does fusion become complete. (The relationship between mean luminance, modulation level and the CFF will be considered in more detail in Section 4.3).

An additional effect which must be considered when investigating transient phenomena related to peripheral vision is the ability of the peripheral retina to perceive motion. Studies of visual movement perception have been concerned almost exclusively with foveal responses; consequently, data relevant to peripheral responses are somewhat limited. The data that are available[59] suggest that the ability of the periphery to detect the

movement of small stimuli is worse than that of the fovea, but for large stimulus speeds and large target sizes the periphery is as sensitive as the fovea. One may deduce from this that when fixating an electro-optical display only rapid angular rates of change of large areas that occur in peripheral vision may be detected. The implications of this statement are that relatively small changes in either sensor image or symbology present on displays which are not being directly fixated will most probably go completely unnoticed. Only if relatively large areas of a peripherally perceived display image are made to change rapidly will motion be detected.

4.2 Display Visual-Field Size

The spatial interactions which occur within the retina permit summation to occur, with the result that as the area of the display image is increased the ability to perceive flicker is enhanced[60]. An almost linear relationship can be observed between the frequency necessary for image fusion and the logarithm of the area of the retina stimulated, the effect extending over a luminance range of approximately 3 log units. This finding would suggest that displays with large visual-field size, in which considerable areas of the image are continuously active, are more susceptible to flicker than small displays. Additional support to this conclusion is offered by observations on the sensitivity of the peripheral retina to temporal modulations. The sensitivity of the retina of the eye to temporal modulation varies across its area. The fovea is considerably less sensitive to flicker than the peripheral retina[61], where even at 10 degree eccentricities the ability to detect modulations in luminance may be as much as 20% superior.

With the introduction of large field of view displays, the quantity of information imaged on this sensitive region of the retina has considerably increased and careful consideration must now be given to the positioning of transient information within the display image. The tendency to position digital readouts of aircraft systems in the sky region of the image produced by a forward looking electro-optical sensor may significantly reduce image clutter, but if an inappropriate update of the readout is selected the constant change in peripheral stimulation may be disturbing. This is particularly so for transients positioned in the upper portion of the display, as their images stimulate the inferior nasal portion of the retina which has maximum temporal bandwidth. The superior sensitivity in this portion of the retina also means that, in large installations, displays positioned in the upper corners of the panel are most susceptible to perceived flicker. Similarly, on the occasions in which the line of sight is directed to objects at approximately knee level (e.g. throttles), displays normally positioned in the panel just below the straight ahead line will now be in upper peripheral vision and may produce disturbing   cker.

It has already been pointed out (Section 4.1) that a refresh rate of 80 Hz would be sufficient to eliminate most of these flicker effects, even at the high luminance levels required in the airborne environment. However, there appears to be a reluctance to move away from domestic standards and to progress to the higher frame rates more appropriate for aircraft displays. Even if the improved rates were to be adopted, there is an additional effect that may occur which should be given careful consideration: when display images adjacent within the visual field are refreshed at different rates, beating may occur between the temporal modulations present within the two images, producing apparent low frequency flicker which has been shown above to reduce operator performance. This effect can also be easily removed by ensuring adequate synchronisation of display images, but this has serious implications for display systems where sequential address is used to reduce the computing capacity required.

4.3 Monocular, Biocular or Binocular Viewing

Not only may temporal modulations be summated within the retina but additional summation may occur centrally within the brain to allow integration of information across the two retinae. The result is a modest elevation in the ability to perceive flicker when the two retinae are stimulated by temporal modulations which are in phase and a modest decrease in flicker detection when the modulations are 180 degrees out of phase[62]. This decrease in flicker detection becomes even more significant when a continuous stimulus is presented to one eye and a discontinuous stimulus is presented to the other eye[63][64]. Under these conditions further reduction in flicker detection may be achieved by increasing the luminance of the continuous stimulus and ensuring that both stimuli are of the same colour.

These observations have particular relevance to stereo television systems and helmet mounted displays. In the former it is important that the independent images presented to the two eyes be out of phase with each other if the possibility of induced flicker is to be kept to a minimum. This implies that a device which uses two synchronised displays should be more susceptible to flicker than a system in which two images are sequentially presented on the display surface and optically switched to the requisite eyes. The precise phase relationships adopted are important if the beating phenomenon described in Section 4.2 is to be avoided. In helmet mounted displays the presence of a monocular viewing arrangement should reduce the ability to detect flicker within the display image; however, the effect of a continuous image in the other eye is difficult to determine, as it will be dependent upon the colour and luminance of this image, and these in turn are determined by the operational role for which the system is conceived.

It should be emphasised that the effects described in this section are relatively small and should not significantly influence the choice of viewing conditions selected by the designer.

4.4 Display Luminance

This attribute of the display becomes somewhat complex when temporal modulations are considered. The luminance of the display image may be described not only in terms of the average luminance over time but also in terms of the peak luminance, its duration, its rise and decay times and the duration between successive peak luminances. Each of these factors affects the temporal modulation function of the visual system.

When continuous sinusoidal modulations centred around different average luminance levels are displayed, the CFF plots produced by the observer closely resemble the spatial frequency plots (Section 3), with maximum sensitivity occuring between 10 and 30 Hz[65]. When the average luminance is reduced, a substantial reduction in the ability to detect temporal luminance modulations occurs. At very low luminance levels fusion may occur at a frequency as low as 10 Hz, but at the other extreme, when the average luminance is very high, frequencies between 80 and 100 Hz may be necessary to maintain fusion. One may be tempted to interpret these extremes of frequency as the refresh rates required for displays to be used for night and daytime applications respectively, but rarely, if ever, is the display modulated sinusoidally in a regular manner in the operational environment. The effects of the temporal distribution of the luminance must therefore be considered when assessing adequate refresh rates.

Luminance discontinuity is usually discussed in terms of the light-to-dark ratio. Using this descriptor, a continuous image would have a light-to-dark ratio of 1:0 and an image with a 50% duty cycle would have a ratio of 1:1. When this ratio is systematically investigated a number of interesting effects are observed. As would be expected, the higher the light-to-dark ratio the nearer the perceived brightness is to that experienced when a continuous emission is observed. However, at a ratio of 1:1, rather than observing a reduction in perceived brightness, which would be expected if a simple integration process were in operation, a peculiar enhancement effect occurs and results in a brightness sensation approximately twice that produced by a continuous emission. Beyond this value large changes in the ratio are required to produce only small changes in the temporal modulation necessary to maintain image fusion. The frequency required for fusion increases approximately linearly with increase in the logarithm of the relative duration of the dark interval.

The fact that the frequency required for fusion depends on the light-to-dark ratio has major implications for the design of optimal displays, particularly of the raster scan type. In most solid state displays flicker does not present a major problem, as the refresh rates employed are sufficiently high to maintain image fusion even when the light-to-dark ratio may be very small. The major difficulties arise when images are generated on CRTs, where interlace and phosphor characteristics have large effects on system performance[66]. Data are available which show the interrelationship between interlace technique, phosphor type and the refresh rate required to prevent flicker[67], but these data are somewhat limited in that they were obtained at luminance levels below those which may be employed in some airborne applications. This limitation means that although the data are useful in enabling one to select phosphor types permitting a reduction in refresh rates, the absolute rates specified are too low for use at high display luminances, where the operator's ability to perceive flicker is increased.

The high refresh rates required to eliminate flicker at high image luminances require the use of increased bandwidth in the display electronics, which may introduce masking noise into the display image and hence seriously affect operator performance[68]. The display designer is faced with evaluating the complex trade-offs which exist between phosphor persistence, refresh rate, system bandwidth and signal to noise ratio to enable him to construct a device which will meet his specific requirements. There is a tendency to reduce the options available by limiting the system bandwidth and selecting a phosphor which has the correct persistence for the expected task. For forward looking electro-optical sensors short persistence phosphors are usually selected, to reduce the image smear that occurs with rapid image motion. The penalty paid for adopting these phosphors is the necessity for high refresh rates and accompanying high system bandwidth, if the system is to be used in high ambient illumination for a task such as air-to-ground target acquisition. Rarely is this penalty paid, and flicker predominates. More often such devices are used in conditions of reduced visibility, where the display luminance is low and perceived flicker is minimal. When image motion is restricted or absent the longer persistence phosphors may be adopted to eliminate flicker entirely.

A phenomenon closely related to flicker, which also results from the temporal properties of the visual system, is line crawl. The perception of line crawl in a CRT image results from the line scan causing apparent bands of brightness. This annoying phenomenon can be considerably reduced by arranging for the sequence of retinal stimulation to be such as to harness the spatio-temporal interactions present in the retina. This can be achieved in displays using short persistence phosphors by discarding sequential interlace and employing staggered interlace techniques.

4.5 Display Colour

The ability to perceive flicker in images of equivalent luminance but of differing colour is not always equivalent. The major differences are caused by the differential sensitivity to specific wavelengths that occurs when the eye is in different states of adaptation[69]. In scotopic vision, the ability to perceive flicker is markedly wavelength dependent, the short wavelengths having to be displayed at much higher frequencies than the long wavelengths to maintain image fusion. In the photopic region little wavelength specificity is observed until very high luminance levels are reached, when the frequencies required to obtain fusion are highest at 575 nm and lowest at 535 nm. From this one may conclude that, at high luminances, with central fixation, green display images are more effective in reducing flicker than images of any other colour.

Display image colour may be considered to have a relatively insignificant effect on the operator's ability to discern temporal modulations. Only in scotopic vision does wavelength play a significant role in flicker perception, but this rarely affects the choice of display emission, since at these low luminance levels the frequencies required to maintain image fusion are so low (approximately 15 Hz) that even the modest refresh rates employed in CRTs are sufficient to maintain fusion.

Another very important factor which influences the spatial frequency resolution of the visual system by affecting the temporal characteristics is the presence of translational and rotational movement between the display image and the eye. This movement may be the result of voluntary actions which occur during visual search, or may be involuntarily induced by the presence of vibrations which cause both the display and the man to move. Both effects are extremely complex and limitations on space do not permit them to be discussed here. The reader is referred to two excellent documents[70][71] which deal most thoroughly with these subjects.

5. CONCLUSIONS

It is not suggested that it is possible at this point in time to assess an operational environment and formulate an ideal display design specification based solely on human performance data. The data available in the experimental psychology literature are all too often inadequate to allow them to be incorporated into a system where complex interactions of parameters occur. It would appear, however, from the way in which it has been possible to utilise relatively simple data to make recommendations on the selection of display parameters, that the overall strategy has significant credibility. It is hoped that, in the limited space available, it has been possible to expose the display designer to some of the problems that he will encounter when eventually the operator is introduced into the system. It becomes clear that many of these problems can be avoided if he is prepared to expend a small amount of effort to locate data on human performance and carry out relatively simple calculations to convert display image data into units compatible with these performance characteristics. The modulation transfer function approach offers considerable promise in allowing this operation to be achieved.

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INTEGRATION OF SENSORS WITH DISPLAYS

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SUMMARY

The sensors commonly found on military aircraft often provide information for display. The various categories of displays available are described with their signal characteristics, cockpit location and operational uses together with discussion on their particular suitability to provide integrated sensor/display systems.

1. INTRODUCTION

From its title this paper could be expected to encompass a vast array of situations and equipment. We will try to restrict the possibilities by talking about the sensors and displays which are to be found in high performance military aircraft engaged in the tasks of attacking both ground targets and airborne targets (or alternatively, defending against attack from the air).

The point of view taken will be that of a designer with experience of both sensors and displays, tackling not only individual equipment problems but also the problem of integration and their association with the other avionic equipment in the aircraft. Thus we must recognise the need for a satisfactory methodology which can start from a clearly defined requirement and argue logically towards the equipment arrangement that will satisfy this requirement. In the real world it may turn out that the requirement is not clearly defi. or, even known. In such circumstances the designer must define clearly the situation e has assumed - even if this is eventually shown to be wrong, a good methodology will enable him to change the design in a controlled manner. It must also be recognised that digital equipment and digital processing are an important part of modern military avionic systems. It follows that the software which determines much of the system operation must be properly conceived and strongly controlled. This can only be done satisfactorily when there is a good scientific method behind the design process. There are various high level languages dedicated to use with real-time avionic sensor-and-display systems which can be very valuable during a development phase but cannot of themselves produce an integrated concept.

Integration is a word with good connotations but we must realise what is meant and what are the advantages and disadvantages. Broadly, by integration we seek the main advantage of the elimination of unnecessary equipment; by which means we should be able to reduce the price and the weight and to enhance the reliability (resulting in further reduction of the overall life cycle costs); or we may solve a problem that is otherwise insoluble.

A major disadvantage may lie in the difficulty of providing satisfactory (both technically and commercially) interfaces between different items of equipment to be furnished by a variety of suppliers. Note that this problem exists also at the conceptual design phase.

2. SENSORS

The equipment which springs immediately to mind is that using the electromagnetic spectrum. In our chosen aircraft the wavelengths may vary from 100 millimetres to 1 micrometre - a variation resulting in marked differences in the technology employed. Nevertheless, these equipments are all used for the purposes of detecting the existence of objects (which we conveniently think of as targets), recognising these targets (tanks or personnel carriers?) and if possible identifying them (theirs or ours?). Note that in some cases the equipment is active but in others it is passive.

The information from the sensor will be displayed on some surface or surfaces and this process is the subject of the paper.

Other sensors are concerned with determining acceleration, velocity, position, direction of the aircraft itself, or of the pilot's eyes. Such sensors are also involved with the display of information.

2.1 Electro-optical

The first of the passive sensors is television, often low-light television in order that it can extend the fraction of the day during which the aircraft can operate. It produces an image that can be shown either on a head-up or head-down display. The line of sight must be directed either by moving the complete camera or, better, by interposing a space stabilised steerable mirror. Using a camera with an optical system permits the use of a zoom lens. A pointer or marker, track stabilised and adjustable by the pilot, appears on the picture.

The appearance of the display depends on system parameters and therefore on the operational requirements. Basically an extension of the human eye, the definition must be adequate for detection and recognition. Thus the stabilisation and pointing accuracy must be good and the line standard suitable. Stabilisation by physical movement may be augmented over restricted angles by picture processing at the display itself.

Broadly there are no dedicated displays in the cockpit so that each acts as a television monitor operating on an agreed standard (FIG. 1). Commercial television standards offer the first obvious choice, but frame rate may be too low and produce unacceptable flicker. Furthermore, in the pursuit of higher definition a larger number of lines may be desirable. Whereas the "optical" sensors (TV and IR) may take advantage of the higher line standard, it is doubtful that radar definition can take similar advantage. Hence the systems designer in his desire to integrate sensor with display is faced with choosing a little used line standard or choosing the standard and suffering some loss of performance.

This choice may (certainly in the future when more powerful processing will be more readily available) be influenced by the addition of image processing equipment. Such a device improves the apparent definition of the picture by operating on the stored picture elements by previously defined rules.

2.1.1 The operation of a thermal imaging device is not unlike television in principle but there are practical differences which affect integration.

The picture is currently formed by a small number of detectors capable of showing small temperature differences, which are scanned over the scene by a device similar to John Logie Baird's mirror drum. The result may not conform to a CCIR television standard so that an electronic scan converter must be employed. However, as mechanical scanning progresses in speed, the so-called half-standard of the Post Office videophone is obtained.

Subjectively, the picture produced from an IR sensor seems to be about the same standard as television.

Typically the wavelength of operation is about 10 micrometres needing germanium optics which would be unsuitable for other electro-optical devices and therefore a bar to integration.

Whilst the integration of television and a thermal imager may be unlikely, a laser sensor to measure range may be required. The chosen wavelengths of operation must allow common optics.

We must not forget that the integration of sensor and display must have due regard of the overall economics of the situation.

2.2 Radar

2.2.1 Radar (FIG. 2) may be used to investigate either airborne or ground targets and each situation places its demands on the display.

2.2.2 Airborne targets are essentially point targets whose relative position and behaviour are to be displayed. Most forward looking airborne radars (FIG. 3) scan mechanically at a slow rate. In order to increase display brightness a scan converter is used and this fits in well with the universality of display surfaces which also demands a single television standard. Note that the signal displayed will be synthetic because of the processing carried out by doppler signal processors, scan converters, etc.

The displayed signal may be used to give direction to another sensor (LLTV as visual identifier) and the process of integrating adequately the two sensors must be considered carefully.

The radar may have to deal with several targets at a time, leading to the process of marking, track forming and threat evaluation. The latter is most important and may require the integration of signals from various sources. For example, by measuring the geometry of the situation and the velocities, directions and accelerations (if possible) of all the participating aircraft, the chances of encounter at all can be assessed. Also the aircraft may be fitted with an IFF* device whose interrogation can lead to displayed information and subsequent recognition. On the display the IFF recognition signal must be properly associated with the processed skin echo.

2.2.3 In looking at the ground the radar may be trying to obtain a map or picture such that a given location may be recognised. The definition of the radar and hence the recognisability of the picture used to be limited by the pulse length and the antenna beamwidth. However, nowadays the use of coherent radar permits doppler frequency discrimination to be used with great effect.

* Note Strictly, IFF refers only to the "question and answer" equipment, but in principle a variety of sensor outputs may be integrated to give an assessment of identity.

For an authoritative description the reader is referred to Skolnik. There is confusion about the terms doppler beam sharpening, synthetic aperture, squint angle spotlighting, etc., but as an illustration it is pointed out that the antenna of a coherent radar may be pointed at the ground (accurately pointed independent of aircraft motion) at, say, 45° to aircraft track. The rate of change of doppler frequency is proportional to the sine of the angle off track. Consequent frequency changes across the beamwidth of the antenna can be analysed by the doppler spectrum analyser and thus effective angular discrimination will be an order better than that provided by the physical beamwidth.

From the display point of view this means that a small area of a coarse definition map may be "blown-up" and show a high definition picture. It is interesting to speculate how far transmitter technology and processing technology will advance, but at the moment the definition of a CCIR television monitor is adequate for the high definition radar picture.

2.2.4 Transmission of radar signals provides the enemy with a good clue about your whereabouts and even your intentions. It will therefore be operationally desirable not to transmit for longer than is necessary. However, it is not a good idea to have an expensive radar on board in a prime situation, but doing nothing. Thus the radar when not used actively to gain information about targets must be used in a passive or listening role. For the radar (and radome) this may mean an extension of the bandwidths over which some reasonable performance may be expected.

For the display two considerations are obvious. It may be desirable to freeze the picture obtained from the last moment of active radar operation (carried out in the scan converter associated with the radar) and it may be desirable to display the signals received during the passive mode. These signals must first be processed (analysed), associated with other signals from a radar warning receiver and an assessment made of the resulting threats. In a high speed, low level, single-seat aircraft it is a difficult decision as to what can usefully be displayed.

2.3 Motion Sensors

Inertial platforms will measure the acceleration, velocity and position of the aircraft but these outputs do not always appear directly on displays. However the parameters are involved with other equipment whose output is shown. Attitude is also available.

The positional output of the platform(s) can be used to drive a map display continuously relating the aircraft to the earth. Currently the map information is stored on film but there are proposals to store simplified maps in a computer memory (see however para. 7.5 showing the excellence of film as a storage medium).

Instructions about tracks to be followed and dangerous areas to be avoided can appear superimposed on the map display in order to direct the pilot. Information arriving in flight can be used to update the display presentation.

2.4 Flight Sensors

Air data may be used in various maps including standby basic flight display. There is an argument whether this facility should be continued in view of the high integrity of inertial platforms.

The act of flying the aircraft should be possible whilst looking through the windscreen at the outside world. To this end the flight sensor information often appears on the head-up display.

2.5 Housekeeping (General Aircraft System)

Fuel supply and engine data must be displayed together with the warning system. Communication must be made controllable.

Included in this section for convenience are the displayed features necessary for the control and delivery of the stores which the aircraft carries.

3. DISPLAYS

3.1 General

So far the introduction of electronic displays in military aircraft as an alternative to more conventional instruments has been slow, conditioned, perhaps, by the rate of change of the aircraft themselves. Although there has been widespread adoption of display techniques in other fields there are some particular difficulties associated with military aircraft such as excessive vibration and a wide variation in ambient illumination.

The instrument and electronic display surface is the primary interface between the crew and a complex aircraft data system. The work load is usually very high and they may well require to observe a number of dials simultaneously. This is one of the reasons why instrumentation in the past has displayed data in an analogue manner rather than digitally in order that changes can be observed

partly by peripheral vision and electronic displays still perpetuate this analogue trend supported by the conservatism of the crew. Pictorial data from TV or FLIR sensors usually calls for high resolution and brightness to improve detection and aid recognition.

Some aspects which must be considered when choosing displays for military aircraft are outlined below.

3.1.1 Space

Since space is at a premium in advanced military aircraft, the accent must be on multi-function capability. The inclination is towards the use of smaller displays with optical magnifiers for head-down displays and collimated displays for head up sights and helmet mounted systems. The latter is particularly important since they do not occupy panel space.

3.1.2 Illumination

The ability to read the display under the widely varying cockpit ambient lighting conditions is a primary requirement and for pictorial data it is essential to preserve grey scale resolution at both extremes. When direct sunlight is present collimating optics can help by preventing it from falling directly on the display face, whilst narrow-band filters tuned to the emission can offer contrast enhancement capability of about 10:1 relative to broad-band reflected light.

3.1.3 Vibration

Vibration affects both man and machine. Even when the whole body is vibrated at certain frequencies the eyeball can also vibrate with respect to its socket. Similarly the display frame will vibrate and the image on the screen may vibrate with respect to the display frame. It is obviously important to avoid co-incident resonances. At present research is being carried out in an attempt to measure the vibration sense and amplitude in real time and to move the image in sympathy to provide spatial stabilisation. Vibration is a contributory factor which has slowed down the use of colour television displays in the military environment (ref. 3.2.1, para. 4) although some progress is being made.

3.2 Types of Display

3.2.1 Cathode-ray Tube (CRT) Displays

In spite of its obvious disadvantage in terms of shape, weight, and electrical properties, the CRT is currently the best display device and likely to remain so for many years.

A wide range of glassware is now available giving screen sizes from 19 mm upwards. The smallest sizes are particularly useful for Helmet Mounted Displays (ref. section 5). Sizes for panel-mounting are mainly limited by the depth behind the panel and an optimum size of about 200 mm diagonal rectangular screen is normal for the average viewing distance in the cockpit. Larger screen areas using tubes up to 600 mm diagonal are useful in observer situations.

One of the most critical factors as already mentioned is to be able to see the displayed data even when the display surface is bathed in direct sunlight to an intensity of 10^5 lux. This implies both brightness and contrast and new high intensity narrow-band phosphors such as P43 can provide this capability especially when matched with a contrast enhancement filter. In this case since the ambient light passes through the filter twice (incident and reflected) but the image only once the corresponding gain occurs.

Unfortunately and naturally the above technique has so far proved very difficult to apply to colour tubes which require broad spectrum transmission characteristics. Colour CRT's have been tried in the military field with varying degrees of success for some time now and brief details are given below of the various types of CRT used.

a) Shadowmask Tubes

This particular CRT incorporates three electron guns (red, blue and green) and its operation relies heavily on the mechanical/magnetic registration of these guns with a mask containing either a dot or stripe pattern interposed before the phosphor screen. So far this configuration is unacceptable for the military environment since the inherent vibration encountered causes loss of registration although some experience and success has been achieved in the less stringent commercial aircraft field.

b) Beam-index Tubes

These CRT's only have one gun and the beam is electronically indexed to colour phosphor stripes thus making it more acceptable to the hostile environment. However these tubes are relatively new in concept and require further development before adoption.

c) Penetron Tube

The Penetron tube operates in an entirely different manner to the others. The screen is constructed of two phosphor layers one red, the other green, with a barrier layer between.   As the beam energy is increased the colour can be modified progressively between red and green as it penetrates through the barrier layer.   This tube, largely because of its mechanical simplicity, is particularly suitable for operation in hostile environments but presents serious problems of adequate brightness especially at the red end of the spectrum due to the reduced beam energy.

To summarise then, no colour tube has yet been produced which can match the monochrome tube in terms of brightness, contrast and resolution in a hostile environment.   Work continues on both cathodes, to provide higher current densities, and more efficient phosphors as well as techniques such as the beam index tube device which shows the greatest promise for the future.   The following sections assume that a monochrome tube is used.

3.2.2 Sensor Matching

At present sensors such as thermal imaging and radar both produce basic pictorial data in a form not ideally suited for direct transmission to a display. Probably the best compromise is to employ a versatile digital scan converter to accept the different scan patterns and data rates from the sensors and to convert them to a form suitable to drive a raster TV display.

3.2.3 Raster Display

Present standards for TV displays are, in Britain, 625 line, 50Hz, 2:1 interlace and in America, 525 lines, 60Hz, 2:1 interlace.   Neither is ideal;   the American version has the advantage of a higher frame rate giving less flicker effect (a particularly nasty peripheral effect) whereas the British has a finer line structure.   Recently there has been a movement towards 875 line rasters and this upwards trend will continue but must be accompanied of course by a similar improvement in sensor devices.

3.2.4 Gamma Correction

It is preferable to fix the gamma (brightness/voltage relationship) of the display.   The implication is that the gammas of the sensors should be matched, at their output, to the display or at least signal processing carried out before it reaches the display.

3.2.5 Resolution

. With recent advances in CRT manufacture the achievable resolution has been increased to typically, 800 - 1000 TV lines/picture height.   However it is important to qualify this figure by specifying other parameters which could limit this performance such as tubes size, picture brightness, position on screen, distortion correction methods and even manufacturing tolerances.   Thermal imaging systems can benefit more by increased display resolution than radar.

3.2.6 Bandwidth

Using the latest techniques in solid state video amplifiers it is relatively easy to obtain bandwidths up to 50MHz.   This offers considerable improvement in horizontal discrimination which is very important for both surveillance pictures and text.

3.2.7 Linearity

The eye is quite sensitive to optical distortions on certain data such as lines or text and corrective circuits and optical techniques such as fibre optic face plates are usually employed to improve the picture.

Linearity and distortions are particularly critical when images are optically combined for accurate correlation (see combined displays).

3.2.8 Panel Displays

Panel displays offer significant advantages in their considerably reduced depth requirements.   The displays using light emitting diodes (LED) and liquid crystal displays (LCD) are very good for alpha-numeric displays and are already widely used.   However, the use of LED's to construct pictorial information is limited both by the maximum size achievable of a monolithic array and the addressing complexity resulting from multiple stacking.

LCD's on the other hand have reflective properties giving a fixed contrast ration, can cope with wide variations in ambient lighting but, so far, have serious temperature limitations.   A matrix LCD providing 100 x 100 elements has been available for some years and reports that a compound matrix 6 in. x 4 in. has been developed for raster display indicates its future potential.

Electro-luminescen. exists in two forms - ac devices incorporating transparent thin films of phosphor and dc devices using powdered phosphor.   The disadvantage of this type of panel is, once again, low brightness output but they are cheap to manufacture, and ideally suited to fixed format display.

3.3 Display Drive

3.3.1 Cursive or Stroke Writing

Cursive drive is produced by deflecting the CRT spot with analogue signals in x and y and controlling the bright-up at the same time.   The advantages of this method are efficiency in light output and resolution and it has been used very effectively in Head-up Displays.   The disadvantage lies in its application to the display of pictorial data and to the integration with digital processing techniques.

3.3.2 Raster Drive

Due to the need to display pictorial information from TV/FLIR sensors there is increasing use of raster generated formats.   Improvements in CRT brightness and the use of higher line standards mean that factors previously against raster drive are no longer valid and the advantages of lower power consumption and digital storage techniques can be fully realised.

3.4 Combined Displays

Whilst it is natural to assume that most displays will be viewed directly, some will require to be optically collimated and also mixing of images whether by electrical or optical means is often desirable.   An example of mixed electrical images can be found in the super-position of variable text on pictorial data. Images from two or more sensors can be mixed optically to provide more comprehension e.g. radar and map matching (see Fig. 5).

3.4.1 Collimated Displays

Head-up displays and Helmet Mounted Displays provide images viewed against a background of the outside world often demanding bright and distortion free pictures. The CRT's used are usually quite small and operate in conjunction with optical arrangements which both magnify and collimate the image.   Advances in this area relate to both the quality of the tubes and the increasing interest in applying diffractive optic techniques in which the narrow bandwidth light output from the CRT phosphor is matched to the chromatic characteristics of the diffractive combiner.

3.4.2 Combined Map and Electronic Display (COMED)

A good example of combined displays is the Ferranti COMED (Fig. 4) in which a coloured topographical map is projected and combined with an electronic display. the map data relating to 1000 NMS x 1000 NMS is stored on 35 mm film which is driven from the airborne navigation computer.   The electronic display overlays the map image with pre-programmed data such as sortie route, threat areas such as SAM sites and may include status of on-board weapon and fuel supplies as well as flight instrument simulation data.   An advantage of this particular optical design (Fig. 5) is that the pilot's head fills the exit pupil and prevents direct sunlight impinging on the viewing screen.

The CRT can also be used to display scan converted radar pictures to provide a map-matching facility.   The map, being driven by the inertial navigation system may be subject to long-term drift and any mis-match registered between the radar image and the map can be used to up-date the system.

4. SYSTEM

Having outlined the nature of some of the "bricks" which can be considered in the foundation of our avionics structure (and others are described in section 5) we had better look at the "cement".   To pursue the analogy further we will examine the architectural design later.   This is not a denial of the essentially "top-down" approach being taken but is intended to make this paper more readable.

4.1 Electrical Integration

We must assume that the interconnection between elements is of a digital nature and the resulting system is defined and controlled by software.   The latter statement conceals a significant problem.

There are various arguments about the style of interconnection which are affected, for example by the size and complexity of the system.   It is prudent however to assume the use of a databus.   Physically "the" databus may be duplicated for integrity and in fact, there may be several - the main, general bus; a dedicated flight control bus; and a bus dedicated to stores management.

At least the participants in the proposed system must agree on the rules governing the databus and it is desirable to have a wider agreement if possible. The rules given by MIL-STD 1553B are the nearest to gaining universal acceptance but not all NATO countries have agreed every detail.   In particular the French and the Germans have reservations.

Our interest is mainly with the integration of sensors and displays.   An important signal from sensor to display is likely to be a video signal (e.g.

output from a scan converter). It is not sensible to load the databus with such a signal because of the high bandwidth involved. Thus video signals would have their own network with such redundancy as deemed necessary to satisfy the integrity requirements. The databus would carry control signals ensuring proper correspondence between sensor and display and dealing with any reconfiguration brought about by failure of some element of the system.

Scan conversion has been mentioned in connection with various sensors and the possibility of unification should be considered although the parametrical requirements are usually sufficiently different to prevent this. Displays show the pictures derived from the sensors but they also show symbology which is related to flying the aircraft, target characteristics etc. When a television raster is used the lines forming the symbols tend to break up - especially when movement is involved. These undesirable effects can be reduced by clever design in the waveform generators. However some users feel so strongly about the need for smooth unbroken symbology that they insist on the cursive writing technique. Thus the system may have to cope with both raster and cursive writing.

4.2 Mechanical Integration

4.2.1 There is little space available in a high performance aircraft fuselage so that pods may be used to carry equipment. Electro-optical equipment and electronic warfare devices are typical examples. In the case of electro-optical sensors where accurate positioning can be essential the use of a wing pod must be thought out very carefully. Obscuration of the field of view by the fuselage is likely.

We have already noted that there can be problems brought about by the integration of, say, a laser and a thermal imager (Fig. 6) because of the different wavelengths of operation. Common optics must be able to deal with such a bandwidth. The materials that can be used (Fig. 7) and also having the necessary structural integrity and capable of surviving exposure to the full slipstream (forward looking window) are difficult and the subject of modern development.

Bearing in mind the need for stablising and pointing the direction in which the sensors look (Fig. 8) optical integration of two sensors is best obtained through the use of a stablised mirror (Fig. 9). The relatively small inertia of the mirror permits a good control performance with high accuracy.

4.2.2 The integration of sensors with a widely different operational wavelength e.g. radar and laser deserves special mention. So far there is no material available as a window (radome) which is sufficiently transparaent to a wide band of wavelengths. Therefore the equipments use separate windows and, integration is the act of unifying the pointing direction. Use of common control circuits is possible and may confer technical advantage but it illustrates a problem which tends to argue in general against integration. Eventually equipments must be procured by some acceptable commercial contractual process by which a vendor has an identifiable responsibility for which he receives a commensurate reward. The process of integration inherently blurs the interfaces of responsibility.

4.2.3 Electronic warfare equipment includes both the passive sensors which detect incident radiation and interprets its meaning and the active devices which are intended to frustrate the enemy either by force or deception.

5. HELMET MOUNTED SYSTEMS

Helmet Mounted Systems have been used for over ten years but until recently have not been generally accepted.

These systems fall into two related categories; sights and displays. A Helmet Mounted Sighting (HMS) System is designed to measure the pilot's line of sight to a target in relation to the airframe and to process that information for use in direct control of weapon delivery systems and remote sensors. The Helmet Mounted Display (HMD) System provides the crew member with a head-up TV display monitor which is lightweight, low-powered, gives high resoltuion and can also be used as a sight. In either case the position and attitude of the helmet must be measured relative to the selected reference frame.

5.1 Helmet Angle and Position Sensing (HAPS)

There are, in general use, three systems which are used to measure helmet angle and position. One is optical, one uses infra-red and the other is magnetic in operation.

5.1.1 Helmet Optical Position Sensing

In this configuration three triangularly disposed LED's are mounted both sides of the helmet arranged so that the lower LED's are parallel to the pilot's line of sight. The LED's are viewed with two V-slit cameras positioned either side of the cockpit and behind each V-slit is a linear charge coupled device (CCD). Each LED is flashed cyclicly and the CCD detects the co-ordinate position of each and computes the helmet angles. The effects of ambient illumination are claimed

to be eliminated by storing the CCD light pattern with, and without, LED flashing and computing the difference.

5.1.2 Helmet Surveying System

This system is similar to the optical unit described above in that a number of infra-red detectors are mounted on both sides of the helmet. Two sensor surveying units (SSU) are hard-mounted on each side and generate pairs of thin, collimated, fan-shaped infra-red beams which rotate at a constant angular velocity and generate pulses from the helmet detectors. The elapsed time between the helmet pulses and a reference pulse together with the angular velocity of the beams is then used to compute the helmet angle.

5.1.3 Electro-Magnetic Systems (SPASYN)

The most recent development in Helmet Angle and Position Sensing Systems is the SPASYN - or Space Synchro - which operates on similar electro-magnetic principles to those associated with rotary synchros but applied to full three dimensional space measurement and involves a closed (or open) loop transducing and computing system. This gives a precise and continuous measure of the relative position and orientation between two independent co-ordinate frames - the aircraft and the helmet.

The system comprises a small three-axis electro-magnetic radiator attached to the airframe and an associated miniature sensor mounted on the helmet. The radiator provides a magnetic field which induces output signals from the sensor. These are computed to determine the position and attitude relative to the radiator. The associated electronics unit contains a microprocessor which is programmed to remove errors introduced by the variation in the environment of different aircraft types.

Of the various systems described both the optical and the infra-red use devices on either side of the pilot which occupy useful cockpit space and are emissive in nature. The SPASYN however is very small and lightweight, gives unlimited angular coverage, is probably more accurate, gives a greater dgree of freedom to head position.

5.2 Helmet Sight

For the helmet to operate as a sight it is necessary to have an aiming mark.

5.2.1 Sight Display

The simplest possible sight is an illuminated cross or circle whose image is focussed at infinity.

The image source can either be a graticule illuminated by a miniature lamp or an LED matrix array. This image is then projected and focussed by the optics and presented to the eye after reflection from the visor. Latest advances include the use of a diffractive optical element in the visor which both reflects and focuses the image.

Another version removes any heat dissipation problems by remotely mounting the array and conveying it via a fibre-optic pipe to the combiner.

An advantage in using a matrix LED is the flexibility to change the image. In addition to the aiming mark, discrete data such as speed, range, altitude and pressure can be digitally displayed. Also, flashing direction indicators can direct the crew member where to look for a target.

5.2.2 Helmet Sight - applications

The Helmet Mounted Sight allows the pilot to acquire the line-of-sight to a target outside the normal field-of-view of the Head-up Display. This data is then immediately available for use by the Weapon Aiming System or to update the Navigation system by spotting way-points.

In addition both slewable weapons and sensors can be slaved to the Helmet. The pilot's head, in effect, becomes a very sophisticated and ergonomically attractive direction controller thereby integrating the pilot's visual/motor skills with the specialised accuracies of weapon and navigation systems.

In multi-seat aircraft where crew-members are equipped with Helmet Sights there can be a real improvement in inter-cockpit communications. For example, target position observed by one crew member can be signalled to other crew members. Coded instructions can also be passed between crew members in a passive manner.

5.3 Helmet Mounted Display

The Helmet Mounted Display (HMD) (Fig. 10) as opposed to just a Sight, combines a Helmet Angle and Position Sensing System (5.1) with a helmet mounted cathode-ray tube and optics to provide a highly flexible system incorporating many of the facilities to be found in both head-up and head-down displays. Because it is a

quality imaging system, it is possible to present both pictorial and symbolic information together offering a combination of synthetic imaging and sighting information.

5.3.1 Cathode-ray Tube

The recent developments concerned with miniature cathode-ray tubes has ensured that in spite of their size (19 mm dia.) there is no reduction in performance from these devices. Also by mounting a miniature CRT on the helmet close to the eye this effectively provides the equivalent of a much larger panel-mounted CRT with the advantage in saving both weight and power in the process.

Under good viewing conditions the eye can resolve 0.25 milli-radian and it is quite obvious that the performance from the display will fall short of this. It is however very important to get the maximum benefit from the HMD by having as high a resolution as is possible by using a compatible line structure for the picture and high bandwidth.

5.3.2 Optics

Another very important factor associated with Helmet Mounted Displays is that the picture scale and viewing angle should not be compromised by limitations in the optics. The first factor to be realised is that the image to be displayed will be collimated to appear at infinity since it should register with the outside world. Secondly the instantaneous viewing angle should be chosen to suit the application with a suitable exit pupil to accommodate a range of users.

When one bears in mind that the objective of such a design must be to achieve the above specification with the least weight penalty and with minimal obstruction to direct vision, some idea of the problem emerges.

The best solution appears to lie in the use of a diffractive optical element preferrably embodied in the visor which will both focus the image at infinity and operate as a high efficiency (90%) reflector at the narrow band wavelength of the CRT phosphor but offering see-through ability at all other visible wavelengths. It would be appropriate to discuss mechanical aspects here before leaving the optics. The first concerns the weight of the CRT package and optics on one side of the helmet and this should be counterbalanced by a similar weight on the opposite side. The second is adjustment to the optics to compensate for different users. Such an adjustment to ensure that the centre-line of the optics is aligned with the user's eye-ball may reduce the exit pupil size with corresponding reduction in the size of the diffractive optic. Also an interesting solution is to mount the CRT off the helmet and transfer the image via a fibre-optics pipe to the helmet. At present, however, no suitable light pipes exist which will not degrade the picture and at the same time impose undue constraint on the helmet.

So far we have only discussed the provision of a monocular image but there could be considerable advantages in providing bi-ocular or even binocular images to both eyes. This would combat the inevitable binocular rivalry which will otherwise occur and would ensure harmonized viewing by both eyes.

5.3.3 Head-up Advantages

The principal advantage of the Helmet Mounted Display lies in the fact that data is presented to the eye irrespective of the direction of regard. This is particularly important when operating a high speed advanced combat aircraft close to the ground and the data can be conveyed subjectively to the eye whilst the pilot's concentration is focussed on flying. Also in the surveillance operational role both during the day, especially in poor visibility, and at night, the ability to slew sensors directly from the hAPS system so that the sensor is oriented to the viewing direction of the pilot, provides a "head out of the cockpit" capability.

When the combat aircraft is carrying sophisticated weapons and sensors there is all the more reason for adding a Helmet Mounted Display. This should improve the chances of a first-pass attack on a target which is not only difficult to see but will almost certainly materialise outside the immediate scope of a Head-up display. Without the aid of an HMD it would be essential to overfly the target first pass and to attack on a much more vulnerable second pass. It could be a matter of survival.

6. WHAT DO WE WANT

We now come to the "architectural" aspects of the integration of sensors or displays - which in effect is a significant part of the design of the avionics system for the aircraft.

The design will depend on operational needs.

6.1 As our example we will take the role of a low-level ground attack aircraft whose mission is the destruction of a known and specified ground target.

6.1.1 The pilot will be briefed with details of the location and nature of the target (may define the weapons to be used), any information about enemy forces and areas to be avoided. Such information will be encoded in a portable data store to be read into the aircraft system. The display apparatus must on demand be able to show, and thus enable verification of, the information.

6.1.2 Displays will be used in the pre-flight check.

6.1.3 Various flight profiles are possible according to circumstances but we will assume the aircraft flies low (not more than 200 ft. above mean ground level) in order to reduce the chance of detection by enemy radar. In daylight the pilot will avoid obstacles with skill by looking through the windscreen. It may be decided to afford a sensor (or sensors) which measure ground profile along the proposed track and give instructions through the head-up display.

6.1.4 Accurate inertial navigation and a moving map display will permit the pilot to follow his intended track. On the display will be superimposed those areas defined by pre-flight briefing which, it is believed, should be avoided.

6.1.5 At some point the aircraft will be within sensor range of the objective and the information must be displayed so that the pilot may verify and identify the target.

6.1.6 Sensors may also supply parametric information on the target location (range and direction for example) which is used to compute release conditions for the weapons in use. The required steering and release point will be displayed even when automatic. The pilot must always have the facility of over-riding an automatically controlled facility (this argument becomes more complicated when applied to the act of flying the aircraft).

6.1.7 Implicit in the attack is the control of the stores. Their nature will determine the computation; an automatic control will decide stick length, arming, etc. but the status will be displayed continually to the pilot.

6.1.8 Either during the approach to the target or the subsequent escape, the aircraft is likely to be under attack from both ground and air. On-board sensors (main radar, radar warning receiver, etc.) can provide warning and assessment of the threats, display the situation and invite pilot decision or arrange an automatic counter-measure. In the latter case it may be desirable to inform the pilot of the action taken. For example if he was dispensing chaff he would need to keep tabs on the stock available at any moment.

6.1.9 Besides the limits imposed by the requirement to fulfil the mission defined above there are other concomitant limits such as a price limit, weight and space limits, reliability and maintainability requirement.

So intricate is the compromise that the design process will be iterative. It will be better that this iteration is carried out at the "paper" stage rather than when much of the equipment has been physically implemented.

The above constraints constitute the most powerful arguments for the designer to integrate with the sensors and displays.

6.2 We have a requirement to satisfy which demands answers to such questions as:

How many sensors?
What are their specifications?
How many displays?
What are they and how used?

The process of answering these questions properly will not only lead to the design of the system but will ensure the "best" (defined by our own rules) integration between sensor and display.

6.2.1 Despite constraints from limitations of time, political considerations and commercial ambitions, the process of design/integration must be carried out by using a scientific methodology. In fact, although it is not an easy philosophy to persuade the participants to adopt, the desired political, commercial, etc. goals can probably only be reached through the use of such a methodology.

There is probably no single correct method; they are all versions of what the systems analyst calls "flow diagrams". The method advocated here is referred to as functional documentation because of its characteristic that it seeks first to determine the exact nature of the function to be performed and delays until the last possible moment the specification of the exact hardware/software arrangements that will bring about the desired result. It is a picture language which can be made understandable with the minimum of additional explanatory text and thus becomes a very good medium for the recording and transmission of information amongst the participating designers. Whilst its very nature tends to prevent the need for modifications (unless somebody changes the requirement!) it has the property of making clear what the overall effect of any given modification will be and enabling appropriately accurate steps to be taken towards rectification.

As experience grow it is possible that some aspects of the operation will be taken over by a computer operating a high level language. There is a danger that the difficulties of such an arrangement will be just as great as those of the avionics system which it is designed to control.

It is important to realise that these scientific methods of controlling the design of complex avionic systems are not a substitute for thinking. The creation of the design can only come from the excellence and experience of the human designers themselves. Methodology provides a valuable stimulus and method of recording.

6.2.2 The proposed system of functional documentation is not described in this paper but experience shows that if pursued rigorously it is possible to start with a blank sheet of paper and end up with very many sheets which first of all define the functions to be accomplished and then the hardware/software required to implement them. The most difficult trap for the designer to avoid is that of thinking in terms of "boxes" rather than "functions". The second most difficult trap is that of believing that the functional documentation process is that which he always adopted anyway.

First of all the functions demanded of the aircraft may be categorised in broad terms. Then each category may be examined level by level, each level delving into greater detail than its precedent. The integration of sensor and display could be involved in several categories but perhaps none more obviously than the weapon aiming category.

Whilst it is assumed here that we are conceiving a system from scratch there is no reason why the process proposed should not commence at any level that is convenient. It would merely mean that initial constraints would be differently defined.

The important features to remember are:

1. Designers must still design - the system helps them to think logically and record their thoughts so that all can see and understand.

2. Recording is mostly pictorial and thus aids appreciation.

3. The method can be started at any level and stopped at any level and the temptation to mechanise (by computer for example) must be viewed with care.

6.3 We have now examined the constituent elements of the integration of a sensor/display system, the technique of interconnection and the philosophical method of deciding what should be done and how to do it.

Other constraints such as price and reliability must be introduced. Both elements are in fact combined in the process of producing minimum life cycle costs.

It can be argued that maximum reliability is achieved by the use of the minimum possible equipment - what isn't there can't go wrong! But which reliability are we talking about? If it is mission reliability then there are arguments about redundancy and reconfiguration after a fault, which do not necessarily argue for minimum equipment. Redundancy may improve mission reliability. On the other hand peace time reliability - low maintenance costs - may well be obtained from the minimum amount of physical hardware. What of software? How does its reliability influence the system? In a complex system the reliability of software can never be completely authenticated. It is essential however to embark on its design in a controlled, logical and structured fashion.

6.4 Multi-function Facilities

It is obvious with such a comprehensive capability existing in the advanced combat aircraft that the needs of the pilot are to be able to communicate with the avionics as easily as possible and under the best available conditions. Probably the most important device in this respect is the display and its ability to operate in a multi-function capacity.

6.4.1 Control

Control is particularly important not just for data selection but to regulate the quality of picture. First of all it must be easy to choose whether to display Radar, FLIR, LLTV or Flight Management data always assuming these various sensors are present. It should also be possible to combine images from two or even three sources. Having selected the data sources it must be possible to vary both the brightness and contrast to cope with the wide range of rapidly changing ambient illumination normally found in the cockpit. Also it would be advantageous to vary the differential brightness of combined images and to have the option of outlining one image relative to another especially when text is super-imposed on pictorial data.

6.4.2 Environmental Effects

Although this has been mentioned already the environment has an important bearing on the pilot's ability to communicate with his avionics. When one remembers that a lot of the flying takes place at very low level, under far from ideal weather conditions in a high performance aircraft the problems are self-evident. Turbulence and vibration are very predominent. During and immediately after an attack phase, when the aircraft and the man may be subjected to high "g" effects during escape manoeuvres his ability to see can be seriously impaired. As was discussed earlier even without "g" effects, eye ball tremor in an already vibrating human frame resting on an oscillating seat watching a quivering box displaying a moving picture, gives one some idea of what the pilot is up against!

6.4.3 Pilot Work Load

In a single seat combat aircraft pilot workload can easily reach unacceptable limits. Even sitting in the environment and doing nothing is fatiguing in itself. Add to this the concentration required to fly the aircraft at low level, to coarse-navigate his way to and from the target, to find and deliver an attack on that target, to observe intelligence data with respect to enemy defences, concentrations and movements, to monitor his own fuel and weapon reserves and to defend himself from air or ground attack is expecting too much of a human mortal without considerable help.

Some help may already be given by:

- terrain avoidance radar for low-level flying
- inertial navigation system for guidance to the target
- weapon aiming and computing systems incorporating laser ranging for accurate attack delivery,

but this workload should and can be reduced still further to get the best out of existing avionics and to assist the pilot in the important decision making tasks.

This additional help can come from:

- combined map and electronic displays
- infra-red sensors for actual target detection and recognition
- helmet mounted sights for off-boresighting of targets, navigation up-dates and intelligence data
- helmet mounted displays which supplement direct vision by TV or IR sensors display whilst adding aircraft flight and management data
- voice input to the avionics.

However, great care must be taken that the human factors are properly assessed. Dangers lie in physically overloading the helmet with extra gear, in causing eye rivalry with images fed to one eye only and in providing too much data on one picture with confusing results. Assuming these factors are carefully evaluated a considerable improvement on pilot workload and the utilisation of sophisticated aircraft and weapons can be realised.

6.5 Data Communication

Radio Communication, whether it be with colleagues flying at the same time or contact with base, is obviously undesirable. Because it causes radiation it may be detected by the enemy and used by a homing missile to lock-on to the radiation source. Radar, as well as its merits, also is a potential hazard on the aircraft just as it is on the ground. Most aircraft are equipped with warning devices which signal when it - the aircraft - becomes a potential target. Other forms of external "communication" normally found on combat aircraft and integrated with the weapon systems are the IFF facility for interrogation and identification of a potential enemy target and facilities for the detection and decoding of reflected laser energy from a target illuminated by ground forces - known as a Laser Ranger Marked Target Seeker (LRMTS - Fig. 8).

Whatever communication with the outside world is considered necessary and desirable it must be clear, un-ambiguous and secure without the risk of enemy jamming and interception.

6.6 Integration Philosophy

What we really want, of course, is the minimum hardware to serve as many useful purposes as possible and to give the best performance at the lowest price. But the ideal is compromised by existing technological capability. However some progress can be made towards partial integration of both sensors and displays.

So far our assumption has been that sensors and displays are permanently part of the aircraft avionics systems. However, some missiles contain sensors such as television cameras whose pictures are viewed on the aircraft display in

order to provide guidance. In these circumstances arrangements must be made for the necessary signals to pass between missile and aircraft.

6 6.1 Sensors

At first sight it would seem almost impossible to provide any form of integration between

- TV operating in the visible spectrum
- Neodymium/Yag Lasers - 1.064 micrometres
- IR Sensors - 7 - 14 micrometres
- CO_2 Lasers - 10.59 micrometres

The provision of separate windows to permit efficient transmission over the whole spectrum is essential and it is possible to bracket TV and ND/Yag lasers together using a Clacium Fluoride window as well as IR and CO_2 lasers using Chalcongenide in combination with Germanium. (See Fig. 7).

Fig. 6 shows schematically a typical multiple electro-optical sensor system which includes both stabilisation and steering mirror facilites. There is little opportunity for the integration of radar with the other sensors.

6.6.2 Displays

We have already discussed the use of multi-function displays. Perhaps two or even three displays may be necessary with logical combinations of data on each such as thermal imaging with LLTV plus text or Radar with map matching, track and route data.

7. FUTURE POTENTIAL

7.1 Fibre Optics Databus

The feasibility of using fibre optic data transmission in avionic systems has already been widely demonstrated as a result of a number of research contracts. The studies have given an indication of the potential advantages likely to be achieved using a fibre optic system. These are: immunity to electro-magnetic interference, electrical isolation between terminals and wide bandwidth at low cost.

The Fibre Optics Databus System will provide an optical version of MIL STD 1553B as far as data rates, formats and facilities are concerned. The remaining technical risk areas are those associated with the standardisation and approval of component parts in the new system. When this has been achieved a full assessment of the total advantages can be made but will almost certainly lead towards a better and "cleaner" systems integration than exists at present.

7.2 Low-level Flying Synthetic Imaging

Fast low flying seeks to avoid detection by enemy radar. Since the performance of all air breathing aircraft is restricted in the heavy air at low levels, high speed is of itself a protection against being caught by other aircraft (although not necessarily by their missiles).

Successful low flying entails avoiding ground obstacles. In good weather conditions the pilot succeeds using eye and skill. The detection of power cables is probably the most difficult problem. Radar sensors can be used but the definition is too poor to represent the obstacles by other than arbitrary lines. Thermal imaging can be used to provide a "television" picture of the approaching terrain. Note that despite poor definition radar can have the virtue of providing range and thus a degree of early warning. Thermal imaging, as in television produces a monocular view.

Based on the assumption that future technology will progress to the extent that enormous speed and memory capacity can be available on board the aircraft, it is possible to contemplate the use of full synthetic images displayed to the pilots. Such images could be in colour and would be a reasonable facsimile of the actual world.

Aerodromes could be "remembered" and knowing the direction of approach the appropriate view could be presented. Unknown territory would have to be keyed by the sensor in use and the displayed picture would provide perspective.

7.3 Advances in Display

In sections 3 and 5 we have indicated likely trends in panel mounted and helmet mounted displays.

7.3.1 Panel Mounted Displays

In summary, cathode-ray tubes are likely to remain superior to flat-panel

displays for picture-imaging in the forseeable future. Colour CRT's will soon be in the cockpit providing displays with adequate brightness and able to withstand hostile environemnts.

7.3.2 Helmet Mounted Displays

Helmet Mounted Displays show promise and offer considerable potential for further development. Images presented to both eyes with see-through reflective capability will provide both a physical as well as a mental balance. Helmet symmetry is also desirable from ejection considerations. Therefore, if you have a left and right display it may be possible to feed data from two sensors to provide stereo-scopic images. It is possible to imagine this being useful in giving depth visualisation for VTOL aircraft or for more realistic synthetic terrain-mapping techniques.

7.3.3 Inter-active Facilities

As the avionic systems become more and more complex, communication with an integrated system must be made easier. Voice communication has been mentioned as one method of giving commands to the system. Another possible facility already proven in other fields is to inter-act with the display either by pointing at it or by moving a marker to overlay the picture. For example, an instruction list could be displayed on the screen below the picture and by moving a cross to point at the word "fix" and then pointing at a position on the pictorial image - perhaps the target - the co-ordinates of the target could be acquired by the system. The main advantage is that it is fast and slick.

As long as the eye remains one of the most sensitive and active of human sensors the impetus to continue the development of the display surface will remain.

7.4 Automatic Target Detection/Recognition Identification

This is a huge subject in its own right but it is an area in which techno- logical advances will be made and its potential relation with the integration of sensors and displays must combine in such a way that information is presented en- abling him to perform these functions. When such a function becomes automatic then only the outcome of the operation needs presentation. However it is difficult to believe that the pilot will have such unbounded faith in the apparatus that he will forego completely the functions of monitoring and over-riding. Thus automaticity in practice means both styles of presentation must be available with the more basic information being available at choice or as part of the automatic reconfiguring process required in the event of failure.

At this point perhaps we might digress to wonder about the function of the pilot himself in the face of such splendid automaticity. Again this is a wide ranging subject which will not be dealt with here. However it may serve as a timely reminder that the process of integrating sensors and displays must also conform to constraints such as cost and reliability. Whilst technically exciting the complex solution might not necessarily be the overall best compromise.

Detection involves the discovery of a wanted signal amongst many unwanted signals. The atmosphere may contribute difficulty. Advances in processing technology have improved and will continue to improve radar preformance; better electro-optical receivers are/will be available. Thus information may be avail- able at longer ranges.

Definition is also improving as technology advances and with it the likelihood of deriving advantage from the combination of sensors.

Identification may involve the target "signature" - the characteristics imposed on the signal reaching the sensor which are known to be attributable to specific targets. Usage of such characteristics implies a fair amount of pro- cessing (comparison of measured characteristics against the on-board look-up table of known features for example).

7.5 Data Storage

The last few years have seen dramatic improvements in the ability to store data magnetically. Bubble memories are now available to store 64K characters and soon this should move up to 256K. Nevertheless several orders of improvement are necessary before it would be possible to do electronically, what the COMET does so elegantly by using film. When one considers that the whole of northern Europe can be stored, in colour, in one film cassette then some idea of the magnitude of the task can be assessed. Even if the maps are simplified by retaining only important features and stored electronically the ability to store the data in flight would be limited to that associated with a particular sortie and with little flexibility to change that data. The whole concept of electronically stored map information must be supported by a ground-based mission control centre providing pre-flight mission planning and portable data stores which are then transferred into the aircraft's airborne computer.

Perhaps one aspect which could be derived from this data base would be the

provision of route sectional contour information to provide synthetic terrain profiles on the head-up or helmet-mounted display as an aid to low-level flying.

8. SUMMARY

In summary then advancing technology will provide the possibility of integration over a wider field of sensors and activities and the system designer must define carefully what exactly is required.

Fig. :   General Purpose TV display for low-light television and infra-red pictures.

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In summary then advancing technology will provide the possibility of integration over a wider field of sensors and activities and the system designer must define carefully what exactly is required.

Fig. 1   General Purpose TV display for low-light television and infra-red pictures.

CONTROLLER,
HAND, RADAR

CONTROL RADAR,
SET

DISPLAY RADAR

DRIVE UNIT,
DISPLAY RADAR

MAIN RADAR
UNIT
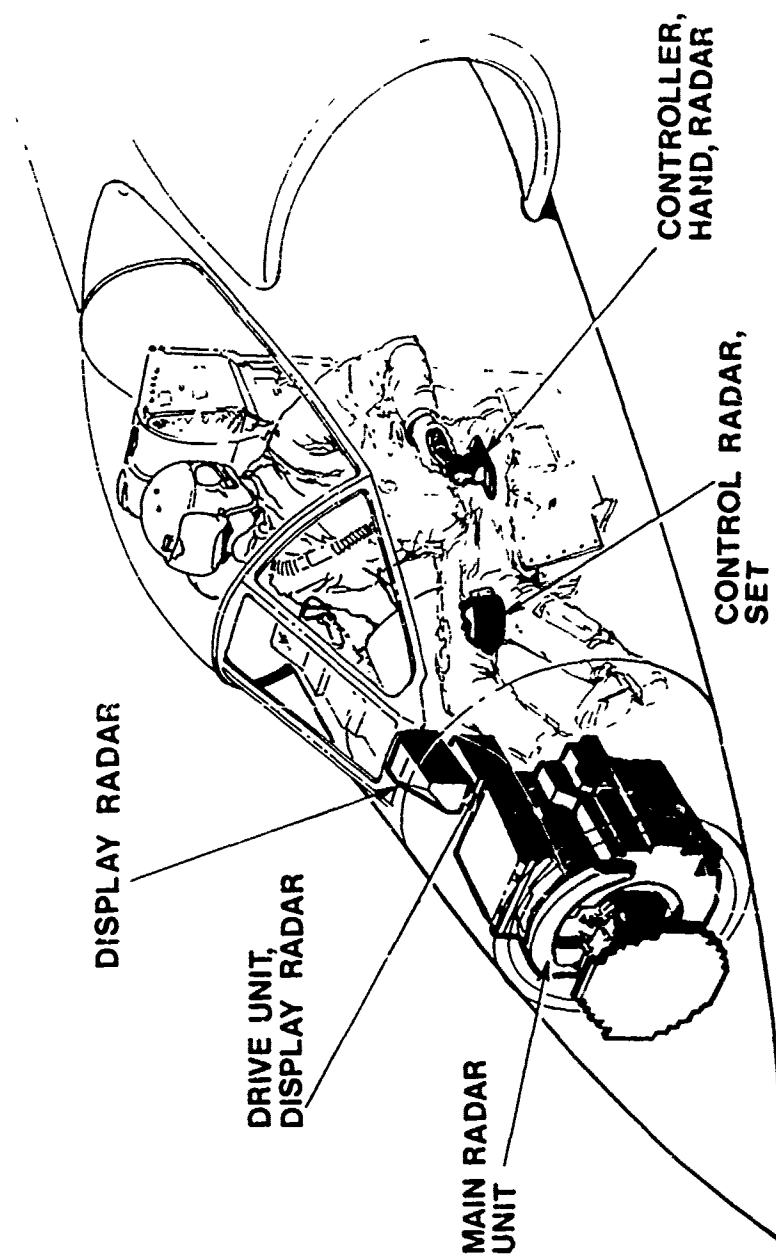
Fig. 2   Blue Fox Radar system installed in the Sea Harrier
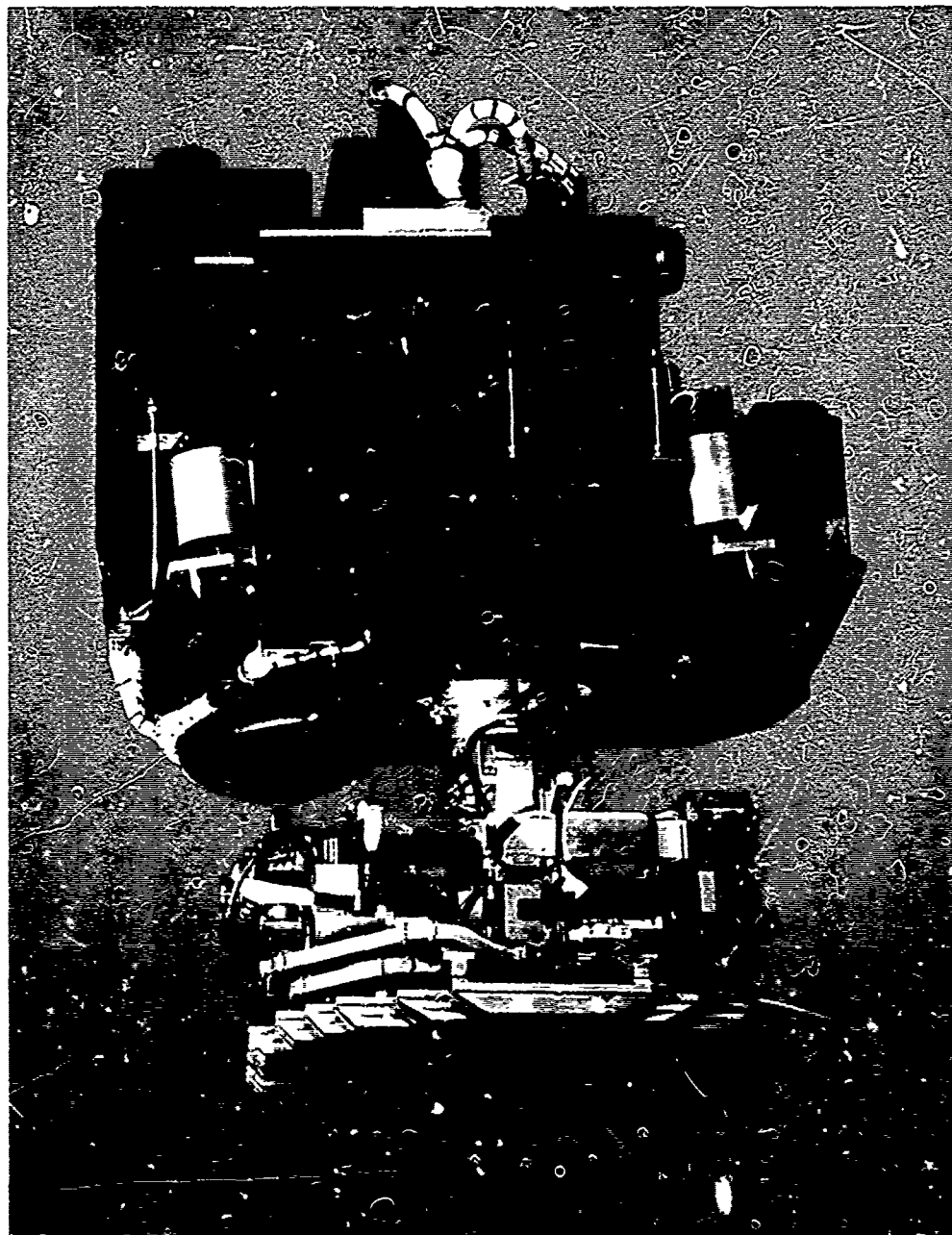
Fig. 3   Blue Fox Radar Scanner

Fig. 4   Combined Map and Electronic Display
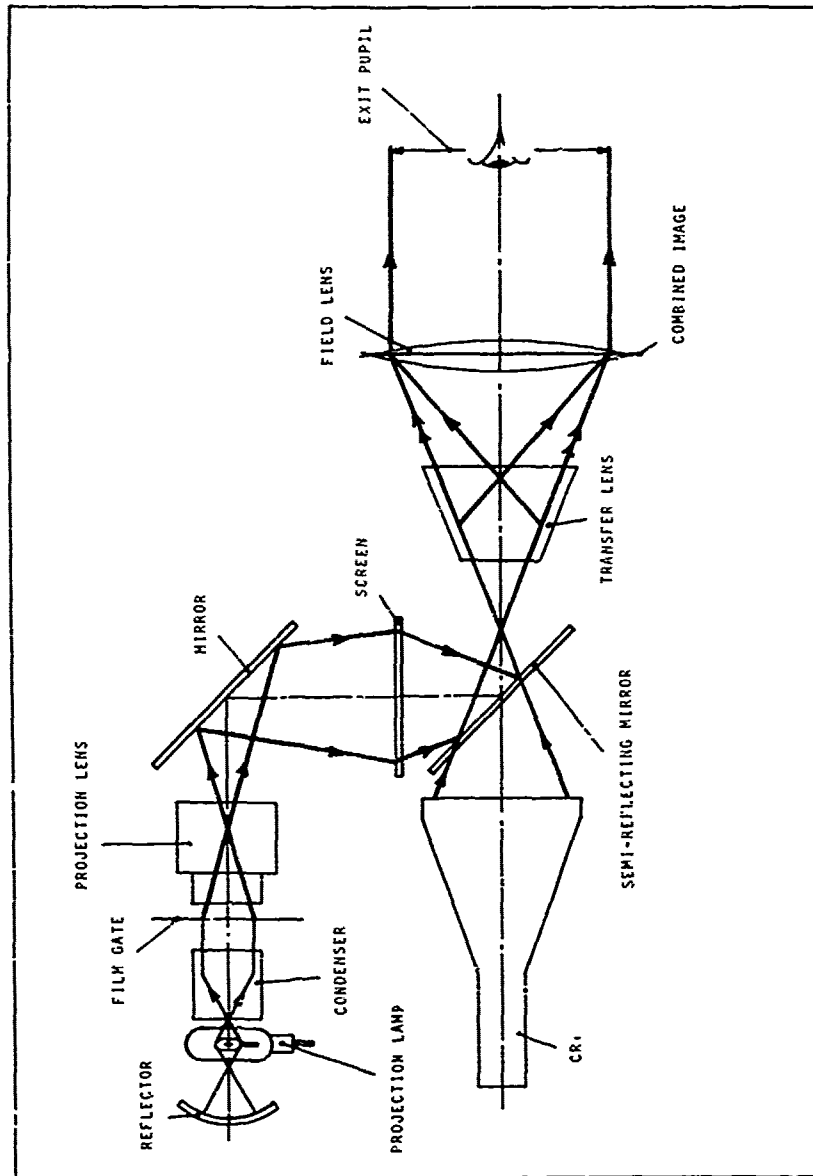
Fig. 5 Combined Display Optical System
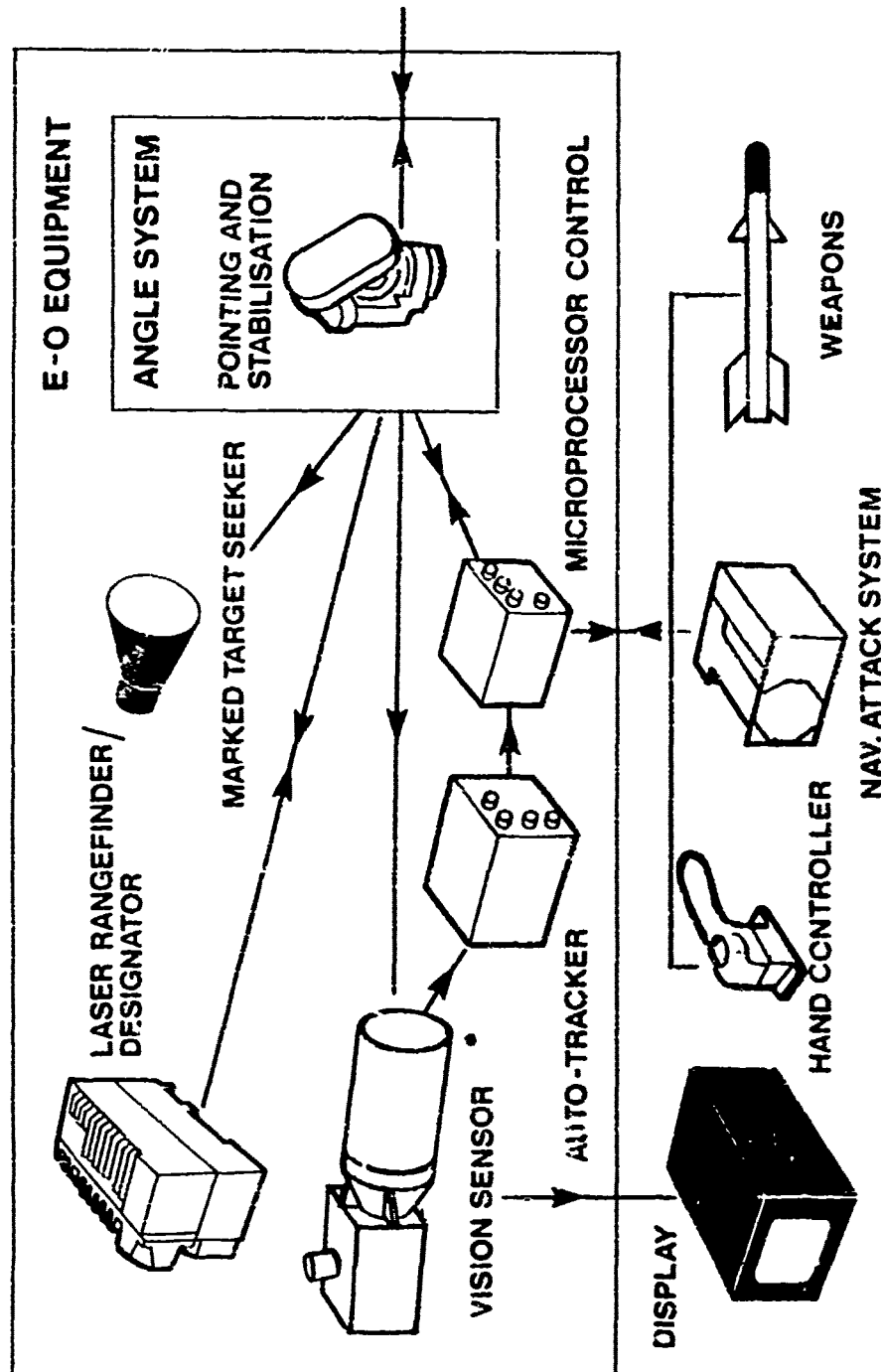
Fig. 6   Typical Electro-optical Sub-System

4-22

Barr & Stroud span the spectrum in the field of Infra-Red Materials
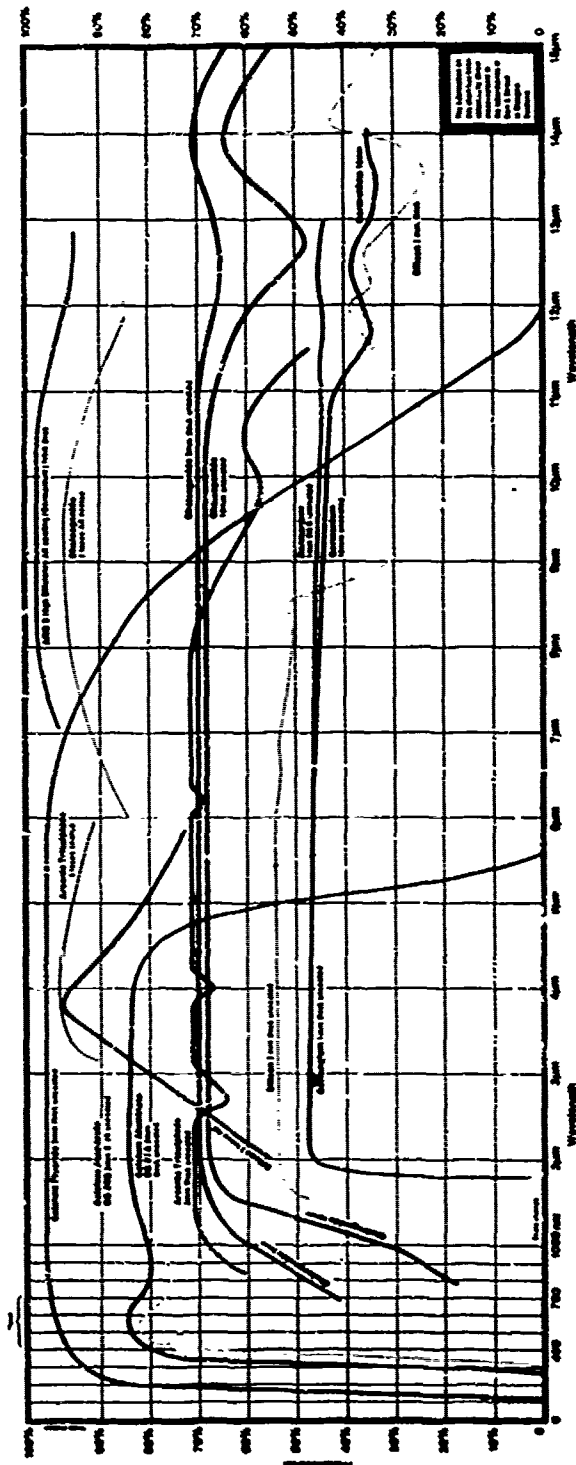
Fig. 7   Transmission Characteristics of Infra-Red Materials
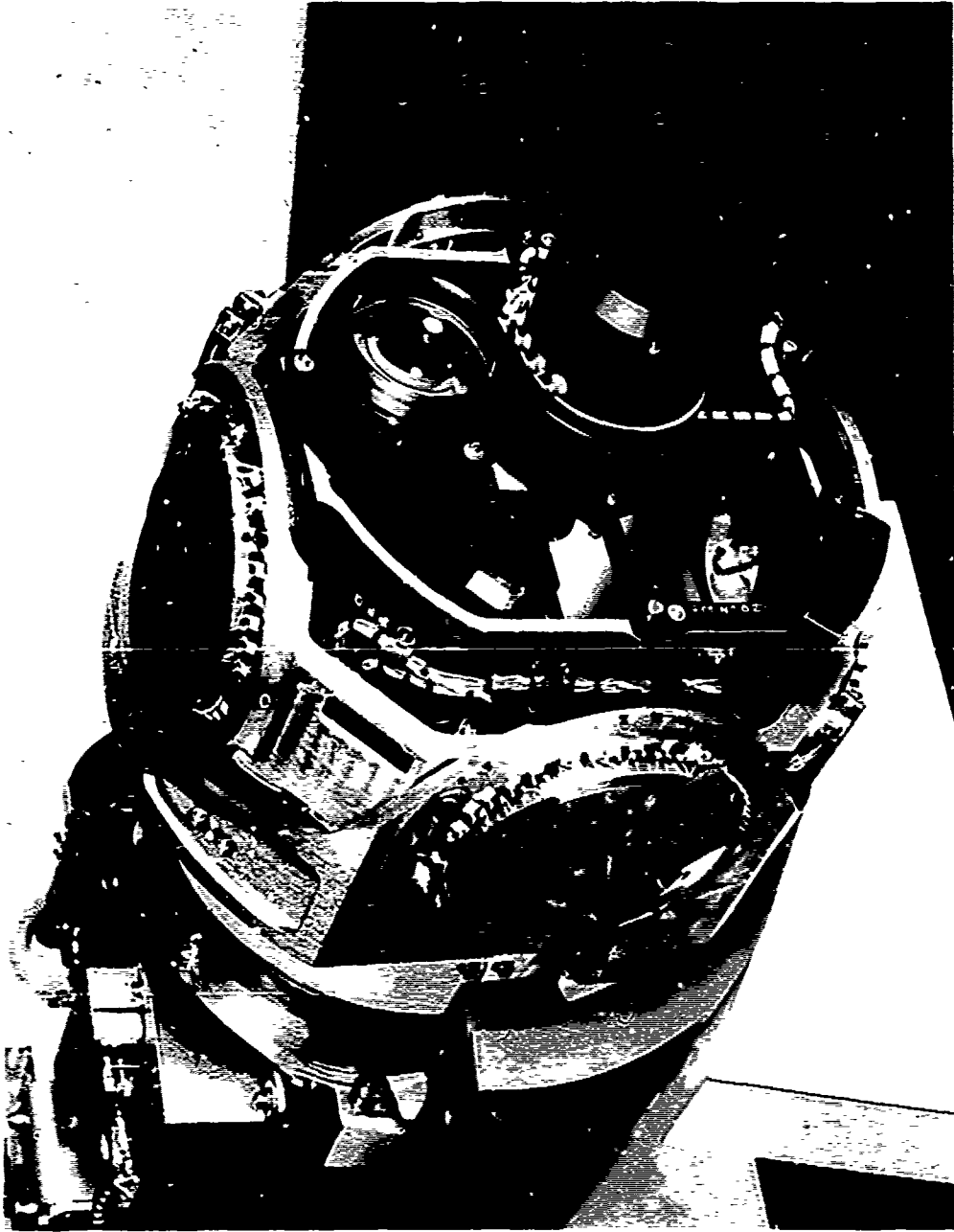
Fig. 8   Laser Ranger Marked Target Seeker incorporating stabilisation and pointing head
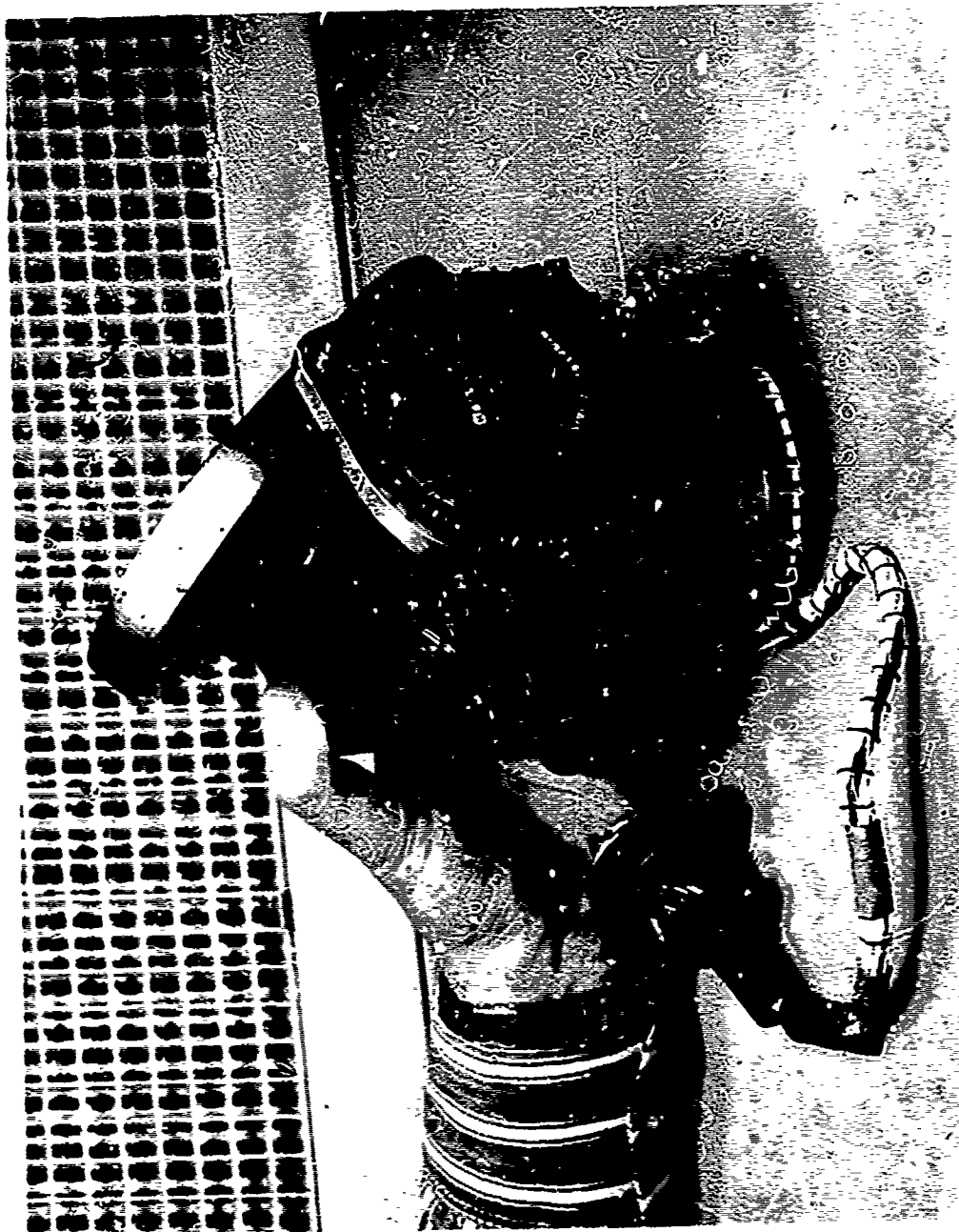
Fig. 9   Stabilised Mirror

Fig. 10   Helmet Mounted System showing helmet angle and position sensor and
projected miniature CRT display

LIQUID CRYSTAL DISPLAYS

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England

SUMMARY

An introduction is given to the physical properties of liquid crystals and the electro-optic effects that may be used for display purposes. A more detailed description follows of both the "twisted nematic" effect, as used in the vast majority of current liquid crystal displays, and of the "dyed phase-change" effect, which is a likely candidate eventually to supercede the twisted nematic display. The performance and limitations of simple, directly driven displays are analysed, and the problems and difficulties associated with more complex, matrix addressed, displays are described. Finally, a brief description is given of a selection of laboratory prototypes and drive methods that demonstrate the progress of liquid crystal research towards solving the various problems associated with high complexity displays.

1. INTRODUCTION

Over the last three or four years Liquid Crystal Displays (LCD's) have had an enormous impact, initially in digital watches and more recently in calculators and other digital instruments. The main advantages of LCD's over other display technologies for this type of application are as follows:-

(a)   the display does not emit light, it merely modulates the ambient light. Consequently it is not only effective in dim lighting conditions but retains its performance in even the brightest ambients where light emitting displays are unreadable;

(b)   the display power consumption is minimal, a few microwatts per square centimetre, so continuous battery-powered operation is feasible over very long periods;

(c)   the effects occur at very low voltages, ~ 3V or less, so very low power drive circuitry is appropriate;

(d)   the cost of displays in large quantity production is very competitive.

In spite of the success of LCD's in low complexity displays for the consumer market, there are many difficulties in making high complexity LCD's and there are many aspects which must be carefully considered when using them in harsher military environments. The aims of this article are:

(a)   to provide a simple background understanding of liquid crystals, the effects used for display purposes, and their limitations;

(b)   to summarise the capabilities of the present generation of production displays;

(c)   to describe a selection of devices demonstrated in laboratories around the world that are potentially capable of extending the range of application of LCD's in the future.

2. BACKGROUND INFORMATION ON LIQUID CRYSTALS

Detailed references are not given in this section; for a more comprehensive review and bibliography, see reference (1).

Liquid crystals may be described as an intermediate state of matter occurring in certain materials between the solid and liquid states, and having some of the properties of both solids and liquids. They are generally composed of long thin organic molecules, and the distinguishing feature of the liquid crystalline state is the way in which the molecules are spatially arranged. In a perfect crystalline solid the relative positions and orientations of the molecules are well defined, whereas in a liquid the relative positions and orientations are virtually random. In a liquid crystal, however, the relative orientation of the molecules remains well defined, but various aspects of the positional ordering of the crystal are lost, as shown in Figure 1. In a "nematic" liquid crystal all positional order is lost, only the orientational order remaining. In a "smectic" material, of which there are several types, the molecules are constrained in layers but are randomly positioned within the layers. "Cholesteric" materials are closely related to nematics, but have a small angular twist between molecules which results in a spiral structure of well defined pitch. In spite of all this ordering, however, liquid crystals are clearly liquid, flowing readily with quite low viscosity. Consequently the orientational order of the molecules is not preserved automatically over indefinite distances as in a solid crystal, but exists typically over distances up to perhaps a millimetre.

SOLID | SMECTIC | NEMATIC | ISOTROPIC
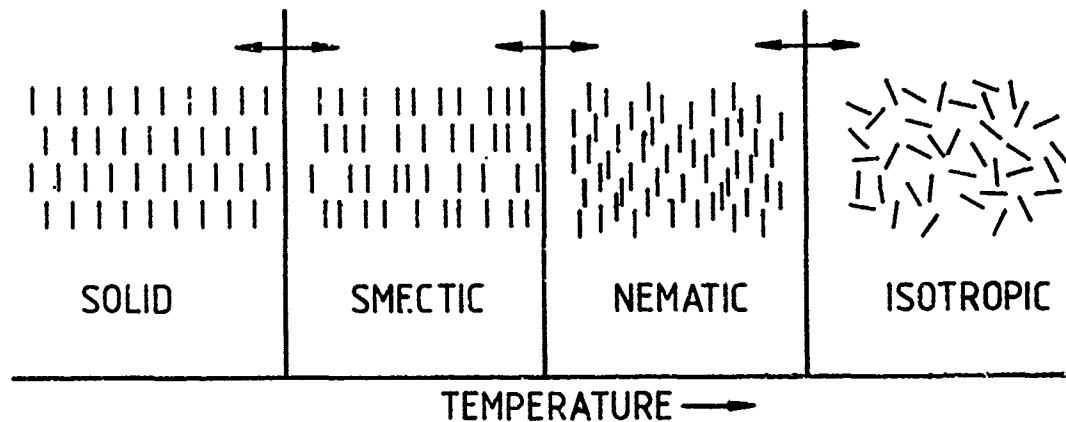
TEMPERATURE ⟶

FIGURE 1   Phase diagram and schematic structures of a hypothetical liquid crystal.

Figure 1 illustrates the phase diagram of a hypothetical liquid crystal, showing one nematic and one smectic phase. In real materials the number of distinct smectic phases may be different, and the nematic phase may be absent or replaced by a cholesteric phase.

An important concept is that of the "director" which describes the local alignment direction of the molecules. It does not refer to the orientation of an individual molecule, since that is subject to thermal fluctuations, but rather it refers to the average orientation of a group of molecules.

A most significant aspect of liquid crystals is the large anisotropy of most of their physical properties when measured in directions parallel and perpendicular to the director. For example, the anisotropy of dielectric constant means that electric fields can be used to control the orientation of the director. This effect is utilised in all the displays discussed later. This dielectric anisotropy may be either "positive" (ie maximum dielectric constant parallel to the director) or "negative", and both types of material have been exploited in displays. The anisotropy of magnetic susceptibility is also significant and permits orientation control by magnetic fields. This is used extensively in research but has not yet been exploited for display purposes. The anisotropy of refractive index, usually between 0.1 and 0.2, is much greater than in most crystalline solids and is the basis of most optical effects used in displays. Other physical properties, such as electrical conductivity, elasticity, visco ity, etc, are also strongly anisotropic and have significant effects on the static and dynamic behaviour of materials and devices.

Finally, liquid crystal materials may also interact strongly with solid surfaces. These effects are also important since, in the absence of electric or magnetic fields, the structure and orientation of thin layers of liquid crystal are largely determined by surface interactions. Methods have been developed of treating glass surfaces with organic or inorganic films, possibly followed by controlled mechanical abrasion, which align the director either perpendicular to the surface ("homeotropic" alignment), or parallel to the surface ("homogeneous" or "planar" alignment) or at some intermediate angle. This control of alignment via surface forces permits very large areas of uniform orientation and texture to be produced, which is also important for the uniform appearance of displays.

3.   LIQUID CRYSTAL EFFECTS USED IN DISPLAYS

3.1   Introduction and Cell Construction

A large number of distinct electro-optical effects have been demonstrated in liquid crystals for display purposes. These include various scattering effects, interactions with polarised light to produce either variable colour or monochrome contrast, birefringence, absorption in dissolved dyes, etc. All of these effects involve molecular realignment caused by the interaction between the applied electric field and the dielectric anisotropy of the liquid crystal. Furthermore, over a wide range of drive conditions it is found that the response of the liquid crystal is determined by the root mean square (RMS) of the applied waveform, rather than by the peak amplitude. Drive waveforms are normally constrained to be AC since, although liquid crystals respond to DC, the presence of DC gives rise to various electrochemical reactions which may rapidly degrade the display.

Before describing the various display effects in more detail it is worth considering the construction of a typical liquid crystal cell, as shown in Figure 2. The figure, which is not to scale, shows the two flat glass substrates which are separated by a uniform space typically between 5μm and 20μm thick, which is filled with the liquid crystal. The inner walls of the glass are covered by the electrode patterns which define the active areas of the display. In transmissive cells both electrode layers are made of a transparent conductor such as an indium tin oxide mixture, whereas in some reflective cells the rear set of electrodes may be metallic. Covering the electrodes are insulator layers of sufficient thickness to protect the liquid crystal from inadvertent exposure to DC. Finally the
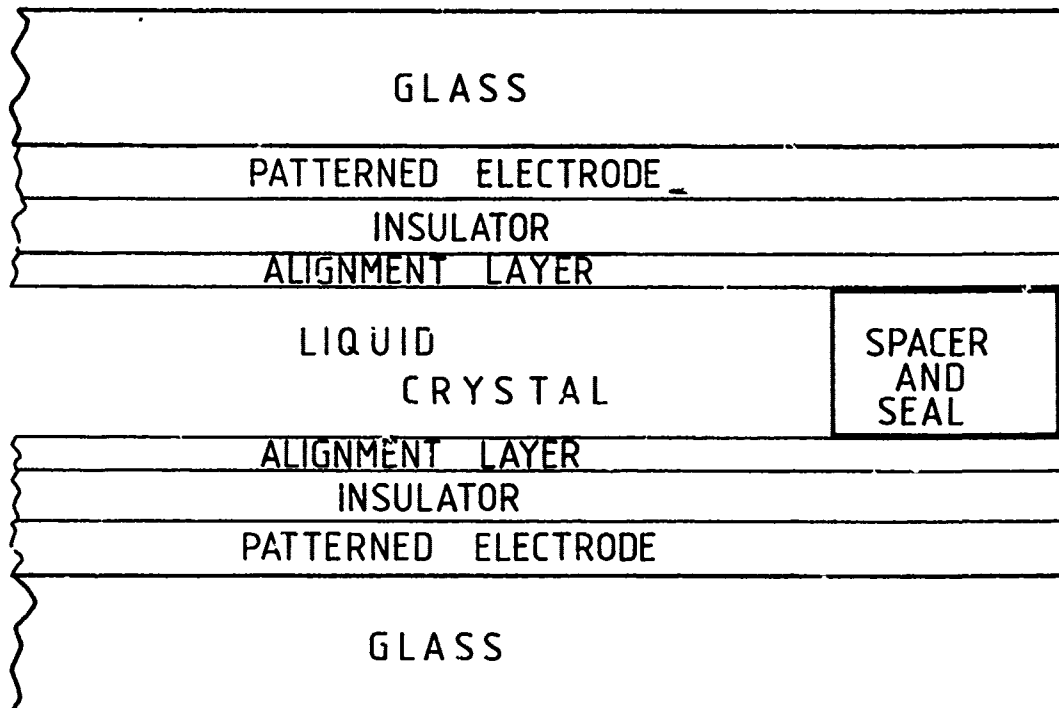
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│                   GLASS                              │
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│               ALIGNMENT  LAYER                        │
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FIGURE 2   Schematic representation of a typical liquid crystal cell. Not drawn
            to scale.

insulators are coated with the appropriate alignment layers if needed. The spacing of the
cell is often controlled by a spacer around the periphery, though rather better spacing
control is sometimes obtained using inconspicuous spacers distributed over the whole area.
The cell is sealed around the edge by either a thermoplastic bond or a higher temperature,
more hermetic, glass-frit technique. The polarisers and reflectors required by some dis-
play effects are attached to the outside of the glass.

3.2   The Dynamic Scattering Effect

It is unfortunate that this effect (2), which was historically the first to be used
commercially, did not give a fair indication of the enormous potential of LCD's.

The effect uses a nematic material of negative dielectric anisotropy containing a
dopant to increase its conductivity. Homogeneous alignment layers ensure that clear
transmission occurs in the undriven (off) state. An applied electric field produces both
current flow and a torque on the molecules. When a critical threshold field is exceeded
a turbulent flow condition occurs. In this state the director alignment is lost and
spatial variations of refractive index occur on a scale suitable for strong light scatter-
ing. The on-state then appears cloudy, but when used in reflection the achievable con-
trast ratio is rather poor.

This effect was soon replaced in most applications by the twisted nematic effect
(described next), largely because of the better visual contrast, longer life, lower vol-
tage operation and reduced power consumption of the latter.

3.3   The Twisted Nematic Effect

A schematic twisted nematic (TN) cell (3) is shown in Figure 3, where a material
with positive dielectric anisotropy is used. The diagram of the off-state shows homo-
geneous alignment on both surfaces of the cell, with these two alignments mutually at
right angles. The director then spirals uniformly from one surface to the other giving
the 90° twist that is used to name the effect. (In practice various defects in perform-
ance are avoided if the surface alignment is not precisely homogeneous, tilt angles of
up to 30° from the surface being used in some instances, but this does not materially
affect the description given here). The front polariser produces linearly polarised
light whose polarisation direction is either parallel or perpendicular to the director
at that face. Because of the large refractive index anisotropy of the liquid crystal
the plane of polarisation is guided through the cell, following the rotation of the
director. It thus emerges polarised orthogonally to the incident polarisation. If the
analyser is perpendicular to the polariser this emerging light is transmitted.

When a voltage above threshold is applied, the director rotates to be parallel to
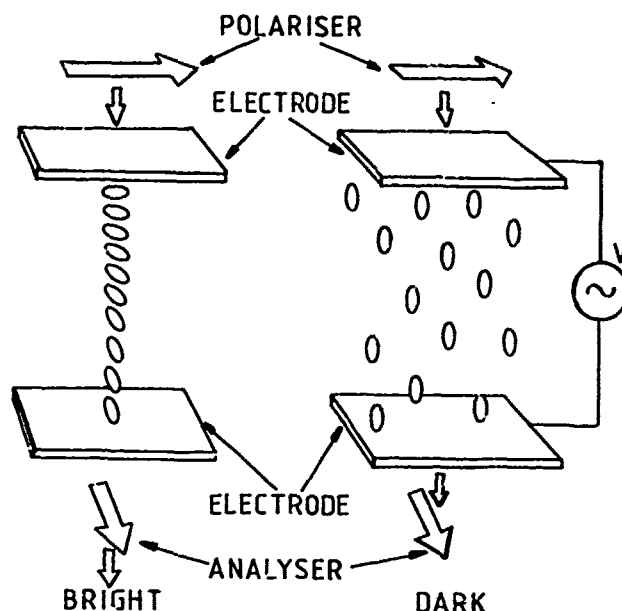the electric field in all places. No guiding of polarisation occurs, so the transmitted

FIGURE 3   Twisted nematic cells in ON and OFF states, used in transmission
between crossed polars.

light is absorbed by the analyser. Of course, by rotating the analyser through 90° the
opaque and transmitting states are reversed.

When the applied voltage is reduced below the threshold value the surface forces
then re-establish the original twisted structure.

The display may be used either in the transmissive mode with an independent light
source illuminating the rear of the display, or it may be used with a suitable reflector
stuck to the rear polariser to reflect the ambient light. In the latter case a diffuse
reflector which does not depolarise the light is required to maximise the display bright-
ness and contrast.

An elegant, low power, solution to night-viewing of reflective TN displays is to
use a "transflective" rear reflector, ie a reflector that transmits say 10% of incident
light. A very weak light source, possibly a beta-light, placed behind this transflector
then gives good transmissive mode viewing in the dark, with a smooth transition to re-
flective mode viewing at higher light levels.

3.4   The Cholesteric-Nematic Phase Change Effect

With this effect (4) no polarisers are required, the display being switched elec-
trically between transparent and scattering states. The cell is filled with cholesteric
material of positive dielectric anisotropy, the cholesteric pitch being a small multiple
of the wavelength of light to optimise the scattering effect. When a field above thresh-
old is applied the positive dielectric anisotropy causes all molecules to align parallel
to the field, the cholesteric twist is lost and the molecular ordering and alignment are
similar to the on-state of the twisted nematic cell. Since no polarisers are used the
cell is completely transparent. When the field is removed the cholesteric twist is
rapidly re-established throughout the bulk of the material. There is then no preferred
direction for the orientation of the cholesteric spirals so a quasi-polycrystalline struc-
ture results which is strongly scattering. Surface alignment layers are not essential
for this effect, but may be used to stabilise the texture of the scattering state.

This effect has a threshold field, rather than a threshold voltage, which is deter-
mined largely by the cholesteric pitch used. It is generally found that cells which give
strong optical effects require somewhat higher drive voltages than twisted nematic cells,
typically 5-10 V.

When used in reflection this effect does not give very high optical contrast, but
quite acceptable contrast can be obtained in transmission. In projection, a simple
Schlieren arrangement will give excellent contrast.

3.5   The Dyed Phase Change (DPC) Effect

This is a direct extension of the above effect which includes dyes, dissolved in the
liquid crystal, to give optical absorption rather than scattering (4,5) The dye mole-
cules must be highly anisotropic, both physically and optically. They must align accurately
with the director of the liquid crystal at all times; this is known as the "Guest-Host"

effect. Also, they must be "pleochroic"; that is, their absorption spectrum should depend strongly on the relative orientations of the molecules and the polarisation of the light. Ideally, absorption should be zero when the optical polarisation is perpendicular to the long molecular axis, and strong when the polarisation is parallel to that axis, as shown in Figure 4.
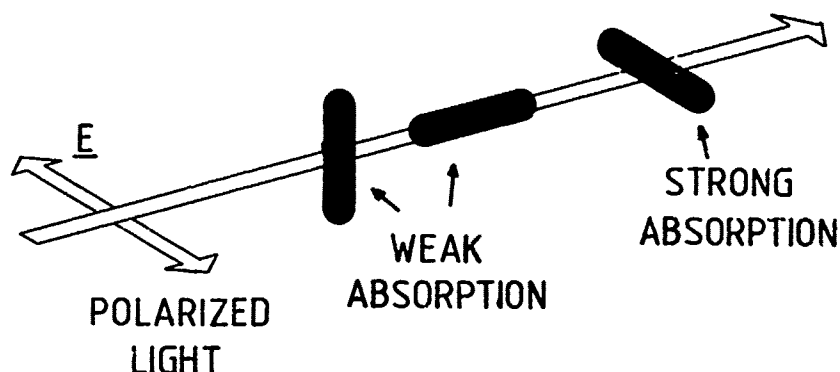
FIGURE 4   The anisotropic optical absorption of pleochroic dyes as used in the dyed phase-change effect.

In the driven (on) state of a DPC cell all the liquid and dye molecules are forced to align perpendicular to the plane of the cell, so light passing through the cell is only weakly absorbed. In the undriven (off) state the twisted cholesteric structure ensures that all polarisations of incident light encounter sufficient dye molecules whose axes are suitably aligned to give strong absorption. As in the previous effect, the electric threshold is field rather than voltage dependent.

With a suitably designed diffuse reflector this effect is visually very attractive. It should be noted, however, that the displayed information appears bright on an absorbing background, the direct inverse of the conventional TN display.

Although dyes of adequate performance are now available, and cell design and drive requirements are well understood, displays using this effect have not yet been exploited commercially to any significant extent. It should be noted, however, that the elimination of polarisers gives not only a considerably brighter display but also one that is intrinsically more stable in a hot humid environment. It is believed that this type of display will be the natural successor to the TN display for a wide range of applications.

3.6   Birefringent Effects

The large anisotropy in the refractive index of aligned nematic liquid crystals permits electrical control of birefringent effects (6). An example is shown in Figure 5, where a thin layer of planar aligned liquid crystal of positive dielectric anisotropy is placed between parallel polarisers. The incident polarisation is set at 45° to the director. By direct analogy with birefringence in solid crystals the transmission may be analysed in terms of ordinary "o" and extraordinary "e" rays polarised perpendicular and parallel to the director respectively. For certain wavelengths of incident light the optical path difference between o and e rays through the liquid crystal will be an integral number of wavelengths and the resultant will pass unhindered through the analyser. For all other wavelengths the light emerging from the liquid crystal will be elliptically polarised, to greater or lesser extent, and will therefore be partially or even completely absorbed by the analyser. Thus, in general, the transmitted light will be coloured. When an electric field is applied the director rotates changing the degree of birefringence and consequently altering the transmitted spectrum. In the limit, for very high fields, the director becomes normal to the plane of the cell and birefringence is reduced to zero.

A similar effect is obtained with negative dielectric anisotropy material in a cell with nearly homeotropic surface alignment. With zero applied volts there is no birefringence and therefore no transmission between crossed polars. As the applied voltage is increased the molecules tilt away from homeotropic and the birefringence rises. Provided this tilt is in a plane at ~ 45° to the polarisation direction this birefringence results first in increasing transmission of white light, followed by a series of colours at higher fields.

These effects are also field rather than voltage dependent, so to obtain uniform effects over large areas requires extreme skill in constructing cells with flat and parallel faces. Effects of this type have only received a limited amount of attention both for alphanumeric displays and for electrically controlled colour filters.

ZERO VOLTAGE
MAX. BIREFRINGENCE

MODERATE VOLTAGE
AND BIREFRINGENCE

LARGE VOLTAGE
ZERO BIREFRINGENCE

POLARIZER   LIQUID CRYSTAL CELL   ANALYSER
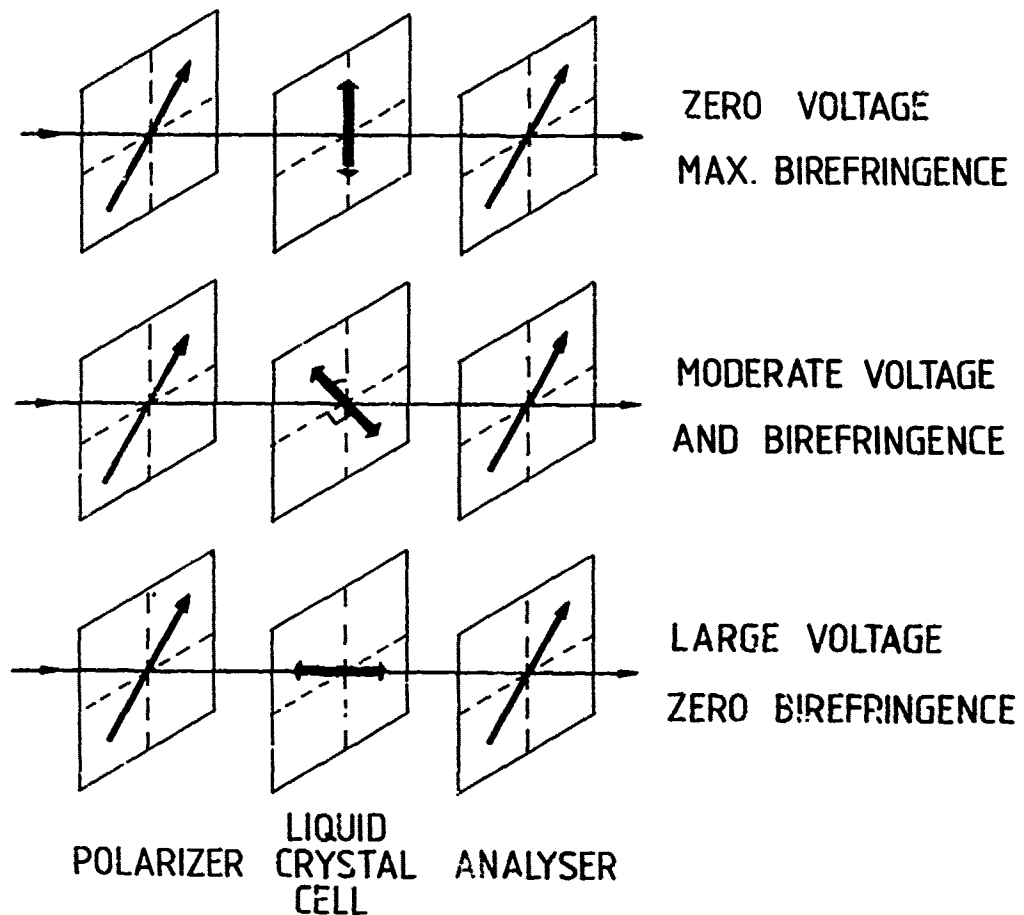
FIGURE 5   Typical "variable birefringence" device at various voltages.

4.   REQUIREMENTS FOR SIMPLE DISPLAYS

4.1   Introduction

In this section the properties of and requirements for simple displays are considered in a little more detail. A simple display is defined here as one in which each element of the display is directly driven with no multiplexing. Attention will be concentrated entirely on TN and DPC displays, but before considering the complete displays it is necessary to consider the acceptability of liquid crystal materials themselves.

In order to be generally acceptable there are many requirements placed on the materials. Firstly, it is vital that they should be non-toxic, both for ease of handling during manufacture and to avoid risks caused by breakage during use. Secondly, they should be highly stable, not only to ensure long life in the operating environment, but also to avoid the need for difficult and costly manufacturing processes. Many of the early liquid crystal materials were suspect on account of either toxicity, susceptibility to atmospheric oxidation or to degradation caused by blue or ultraviolet light. The discovery of the biphenyl family (7), however, has provided a satisfactory solution to all of these problems. Indeed, some manufacturers now claim operational lifetimes in excess of 30,000 hours.

Temperature has many effects on LCD's. The most important consideration is the range over which the material remains liquid crystalline. This is bounded of course at high temperatures by the transition to an isotropic liquid, and at low temperatures by a transition either to another liquid crystal phase of higher order or to a solid phase. The nematic to isotropic transition is well-defined, but solidification is often accompanied by extensive super-cooling. It is most important that the quoted minimum temperature for a material represents melting from the solid and does not rely on supercooling: the super-cooled state is only metastable, and damage to the surface alignment layers is possible if repeated solidification occurs.

Single chemical compounds are rarely liquid crystalline over a usably wide temperature range, but multi-component mixtures have been developed (8) which have nematic phases over a wide range. Figure 6 shows the phase diagram of a two-component mixture of biphenyls, where the eutectic composition is nematic from 20°C to 70°C. By adding precisely determined quantities of other materials a multi-component eutectic can be made with even wider range. For example, the four-component mixture E7 (BDH nomenclature) used in watch displays operates from -10°C to +60°C. More recent mixtures have considerably extended this range and at the same time afforded improvements in other material parameters.
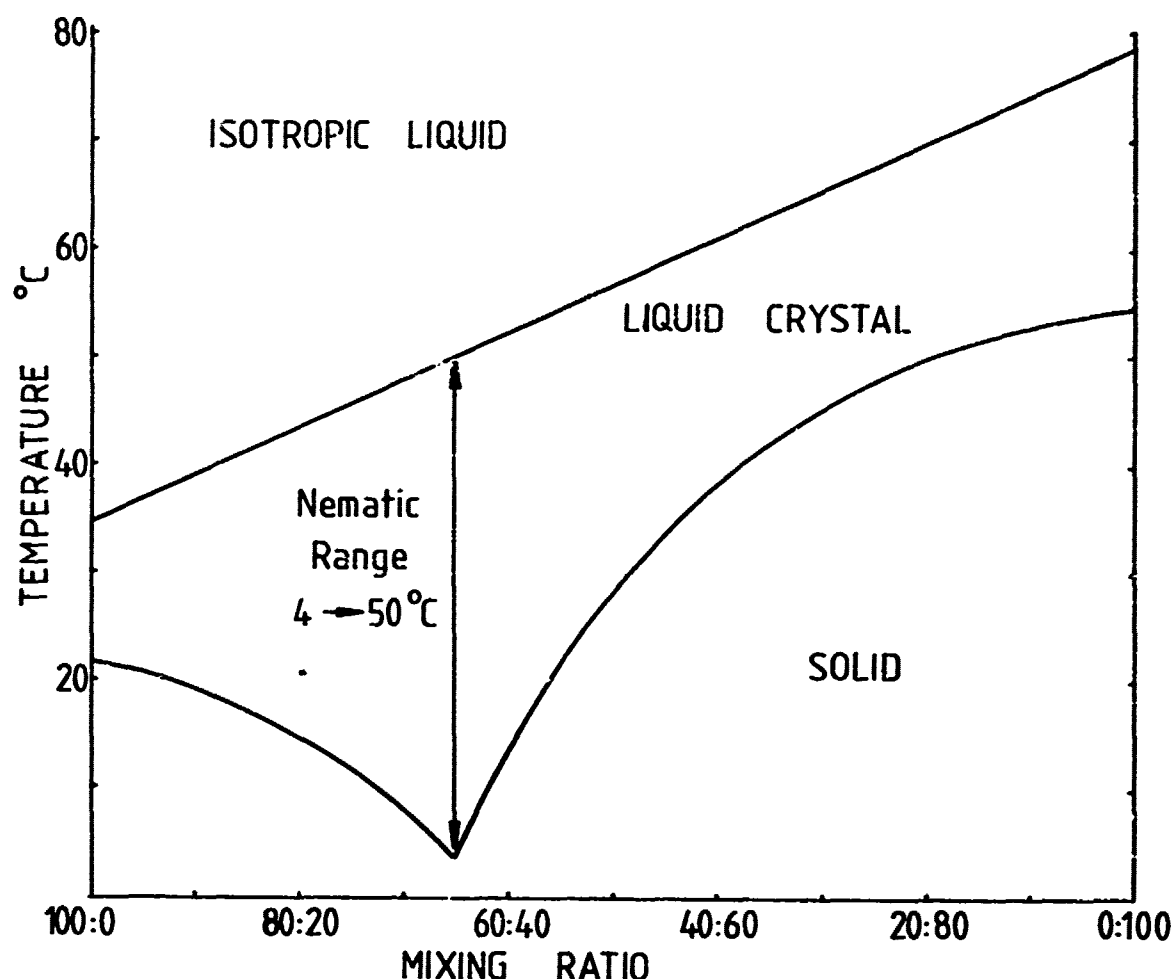
FIGURE 6   F..ase diagram of a two-component liquid crystal mixture, showing the wide temperature range of the nematic phase at the eutectic composition.

4.2   Twisted Nematic Displays

For low power, portable applications, drive voltage is a most significant considera-ti^n. Figure 7 sh.ws the transmission at normal incidence of a TN cell plotted against applied voltage. There is a fairly well defined threshold voltage, $V_{:}$, normally occurring between 0.8V and ^.5V. The transmission then falls to ~ 10% by between 1.3V and 2.2V. To achieve good contrast requires dri.e at about 2 x V_T, although quite usable contrast is obtained at slightly lower voltages. Since power dissipation is roughly proportional to the square of the drive voltage it is clearly beneficial in terms of battery life to operate with low V_T materials. Batteries, however, are available only at certain vol-tages, so the major consideration may often be to match the required liquid crystal drive voltage to that produced by 2 or 3 cells of a specified battery.

Good liquid crystal materials have high resistivity, > 10^{10} Ωcm, so that cells normally present an impedance of > 10^7 ohms per square cm in parallel with 1000 to 3000 pF per square cm. When driven with low frequency AC the power dissipation is consequently limited to a few microwatts per square cm.

The appearance of a TN cell driven slightly above threshold is a strong function of the direction from which it is viewed. This arises because the molecules are constrained to rotate in a particular direction in going from the off to the on state. The threshold voltage for the optical effect is lower than that at normal incidence in one particular viewing quadrant, known as the "low voltage quadrant". From all other directions the threshold is higher. It is therefore most important to obtain the optimum relative posi-tions of display, observer and illumination. The observer should always view from within the low voltage quadrant. The ambient illumination may throw shadows of the displayed data onto the rear reflector. Usually these shadows increase the observed contrast, but if the reflector is a significant distance behind the liquid crystal layer then there may be disturbing parallax between the data and its shadow. In this case the intensity of the shadows may be reduced by illuminating from directions well outside the low volt-age quadrant.

T;e threshold voltage, V_T, of most liquid crystals is temperature dependent, so the
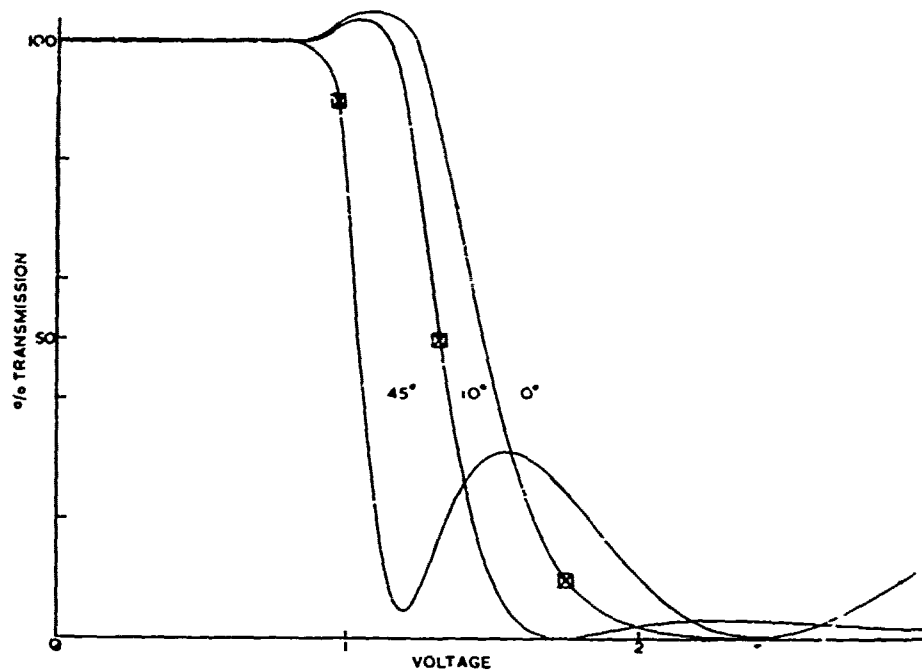
FIGURE 7 Normalised optical transmission of a TN cell between crossed polars as a function of applied voltage at three angles of incidence. The $10°$ and $45°$ data apply to the "low voltage" quadrant.

temperature coefficient, dV_T/dT, is a parameter of interest. Typical values range from -0.4 to -1.0% per $°C$ for TN materials. This effect is not too important for directly driven displays, providing that enough volts are available to turn the display fully on at the lowest temperature, but it is a very significant parameter for multiplexed displays (see Section 5).

Perhaps the most striking effect of temperature is on the response speed of the display. This is determined largely by the viscosity of the material which is almost inevitably a strong function of temperature. Figure 8 shows the variation of both turn-on and turn-off times for a particular TN display as a function of temperature. It is clear
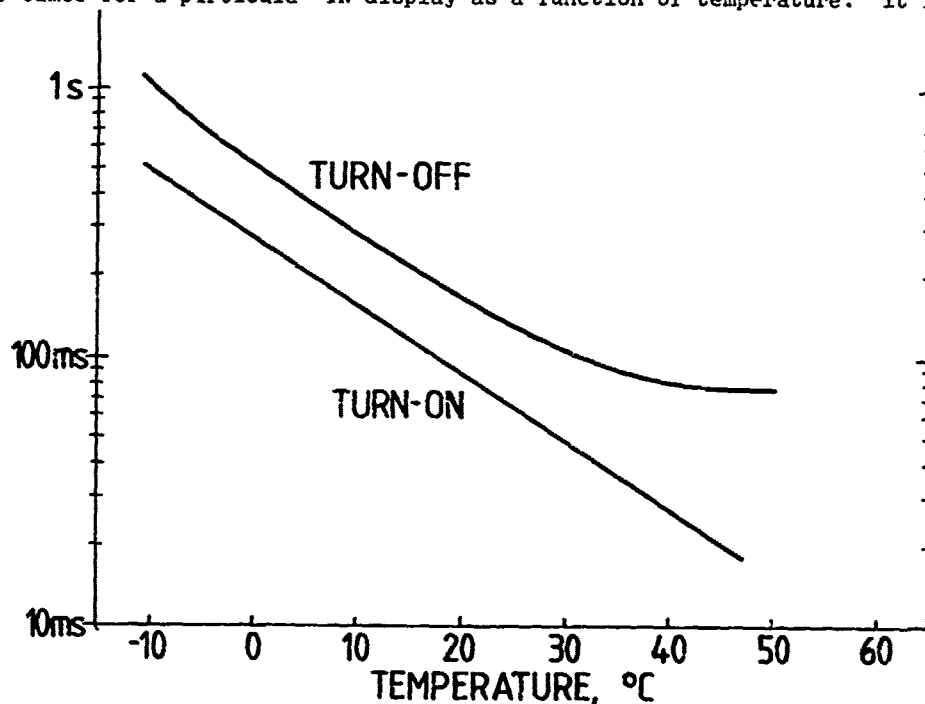
FIGURE 8 Variation of response times of a typical TN cell with temperature. Cell spacing 12μm, material E7. Note that response times are proportional to viscosity and to the square of cell spacing.

that, while rapid response is possible at room temperature and above, response is very sluggish below 0°C. Increasing the drive voltage speeds up the turn- time, but, since the turn-off driving force is determined by the surface alignment layer, one is able to affect the turn-off speed only by reducing the viscosity. In principle one could achieve faster response with a given material by reducing the cell spacing, but in practice this also affects many other aspects of cell design and cannot be reduced. There is, however, a class of materials known as "two-frequency" materials discussed in Section 5.5 where this difficulty is alleviated.

There are many other less significant effects of temperature on liquid crystal parameters, for example resistivity, cell capacitance, refractive indices, etc, but no discussion of them will be included here. The remaining effects of temperature relate to the cell. In general two methods of cell sealing are in commercial use. The first uses a low temperature, ~ 150°C, thermoplastic bond. This is perfectly reliable for most domestic applications but there are doubts about its reliability in harsher military environments, particularly in hot, humid situations. The second uses a high temperature, ~ 500°C, glass frit method which produces a fully hermetic bond capable of withstanding much harsher environments. The TN cell, however, faces the added problem that the adhesion of the polarisers is liable to degrade in hot, humid conditions unless some form of secondary encapsulation is used.

4.3 Dyed Phase Change Displays

In principle DPC displays have two major advantages over TN displays. Firstly, they do not require polarisers and therefore should appear much brighter than TN displays. Secondly, their optical properties are far less anisotropic - there is no "low voltage quadrant" - so they can be viewed clearly over a much greater angular range.

The basic cholesteric materials are made by adding small quantities of "twisting" agents to normal, wide temperature range, nematic mixtures. The temperature ranges and viscosities of the resulting mixtures are therefore very similar to those of the nematic components.

Choice of the dye component involves many considerations. Its alignment in the liquid crystal host is described in terms of an "order parameter" (5) which must as high as possible to minimise absorption in the on-state. Its absorption spectrum must be suitable, blue and black being preferred but not readily obtainable. It must be sufficiently soluble in the liquid crystal host to give adequate absorption and contrast without risk of the segregation of dye particles at low temperatures. Finally, it must be highly stable when exposed to solar UV radiation. Dyes so far discovered (9) which have the highest order parameters have rather poor UV stability and conversely, those with adequate stability have lower order parameters but nevertheless give adequate contrast. These dyes are now adequate for commercial exploitation, but there is scope for improvements in order parameter, solubility, absorption spectra and UV stability.

The overall design and performance of a DPC display is subject to many compromises, since each variable parameter affects more than one of the observable features. For example: a large cell spacing provides good contrast, but at the expense of either slow turn-on or high drive voltage; short cholesteric pitch improves contrast and gives rapid turn-off, again at the expense of high drive voltage; high concentration of dye gives good contrast but reduces on-state brightness and may involve low temperature solubility problems. Clearly, the achievable speed, contrast, drive voltage, etc, will depend strongly on the external design constraints.

As an example, consider a moderately thin cell driven at about 10V RMS. A high brightness display is possible with 10:1 contrast ratio using a high order parameter dye; 3:1 contrast is possible with the more stable counterpart. Turn-on times of ~ 100ms and turn-off times ~ 20ms are achievable at room temperature, which is much faster than the response of a TN display.

Temperature affects the threshold voltage in much the same way as for a TN display. Values of dV_m/dT are of the order of -1% per °C. Similarly response times are affected by changes of viscosity with temperature. However, the fundamentally faster response of the DPC effect means that usable response speeds can be retained to much lower temperatures.

The angle of view of a reflective DPC display is determined largely by the properties of the diffuse reflector. By control of the surface texture of this reflector the on-axis brightness of the display may be played off against the wide-angle appearance. Furthermore, since no rear polariser is required, the rear reflector can be located inside the LC cell, thus eliminating the shadow parallax problems discussed above, and further increasing the brightness and contrast of the display.

The same technologies for cell sealing can be used with DPC cells as with TN cells. The absence of polarisers, however, means that the DPC cell should be less susceptible to degradation in extreme environments.

5. COMPLEX DISPLAYS

5.1 Matrix Addressing

A complex display is arbitrarily defined here as one to which the number of connections is less than the number of individually selectable display elements. For a numeric display using the 7-bar format, a row of ten digits requires at least 70 elements. To supply a

driver and connecting wire to each of these elements is obviously uneconomic. For alpha-numeric displays, where each character requires at least 35 dots, the problem is far more severe. The obvious solution is to use a matrix addressing method. The transparent conductors on both cell plates are patterned so that each electrode is shared between several display elements. The behaviour of this arrangement is electrically equivalent to that of a rectangular matrix of n-rows and m-columns, the cross-points representing the display elements. The minimum number of connections is obtained when n=m,but even with n=5 the number of connections to the above 10-digit example is reduced from over 70 to less than 30.

A simple way of addressing a matrix display is shown in Figure 9. The rows of the
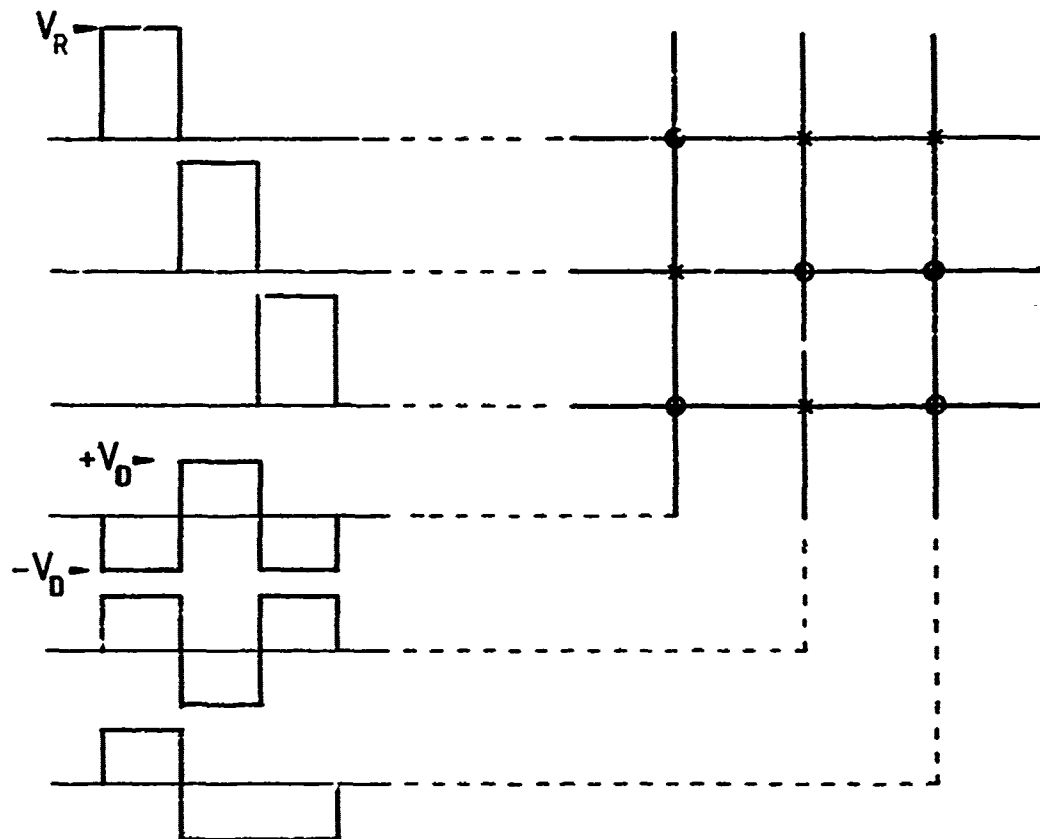
FIGURE 9   Multiplex drive scheme for a 3 x 3 matrix. Scanning pulses, V_R, applied to rows; data pulses $\pm V_D$, applied to columns. Polarity reversal for AC drive not shown.

display are scanned repetitively in sequence by a "row select" pulse of amplitude V_R. While each row is selected the appropriate "select" and "non-select" data pulses, of amplitude $\pm V_D$, are applied to the columns. The liquid crystal elements respond to the root mean square of the difference between the row and column waveforms. Net AC drive is achieved either by reversing ne drive polarity after each scan or by replacing each pulse by an alternating waveform.

The problem now arises that supposedly "off" elements experience a significant drive voltage, largely composed of the data pulses to all other elements in the column. The ratio of RMS voltages applied to "on" and "off" elements, and therefore the display contrast, may be maximised by correct choice of V_R and V_D. Alt and Pleshko (10) have shown that, for a display consisting of n rows, maximum voltage ratio is achieved when $V_R=\sqrt{n}\ V_D$. This relationship is very important for large values of n, but for values of n around four a convenient solution is $V_R = 2V_D$.

The importance of this optimisation is apparent when the liquid crystal characteristics such as acceptable contrast, angle of view and temperature range are considered. Figure 7 showed the transmission versus voltage at both normal incidence and 45° from normal in the low voltage quadrant of a TN cell. Figure 10 shows normal incidence transmission plotted against voltage over a wide temperature range. Satisfactory viewing over a wide angular and temperature range requires:

a)   the value of V_{OFF} must be below threshold at the most oblique viewing angle at the highest temperature;

b)   the value of V_{ON} must give adequate absorption at the steepest viewing angle at the lowest temperature.
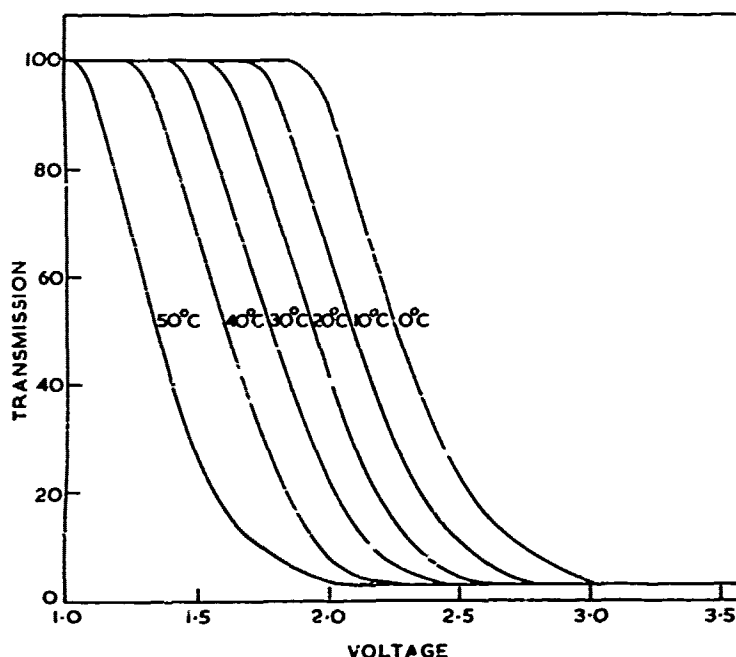
FIGURE 10   Variation with temperature of transmission vs voltage curves of a TN
            cell between crossed polars. Note the reduction of threshold voltage
            with increasing temperature.

The multiplexed performance of a display at a fixed temperature therefore depends on
the steepness and angular dependence of the threshold curve of the material used, which
may be characterised by various figures of merit. For example, the ratio of voltage
giving 10% transmission at normal incidence to voltage giving 90% of maximum transmission
at 45° incidence immediately shows how many lines may be multiplexed at that temperature.
The material E7 mentioned earlier, which was not designed for multiplexing, has a figure
of merit of about 1.9. This is scarcely adequate for even 3-way multiplexing with full
contrast over this angular range. Alternative materials, however, have been developed
with figures of merit less than 1.7 which give quite presentable performance in 7-way
multiplexed reflective displays.

The large values of dV_c/dT of all liquid crystal materials preclude multiway multi-
plexed operation over a wide temperature range with fixed drive voltages. Accurate methods
for temperature compensation of drive voltage have been developed which can maintain the
visual appearance of displays over practically the entire temperature range that the
material is liquid crystalline. These methods either involve a thermistor or other tempera-
ture sensor mounted close to the display cell, or may use the liquid crystal material as
its own temperature sensor. This latter method (11) makes use of the dependence of liquid
crystal capacitance on temperature and voltage, and has the advantage of sensing tempera-
ture at exactly the right place and with no time delays. In spite of the achievable accu-
racy of temperature compensation it is still advantageous to use materials with small
temperature coefficients in order to minimise the effects of temperature gradients across
the cell.

To date, commercial alphanumeric displays have been produced using up to 16-way multi-
plexing of reflective TN cells, operating typically over a 40° temperature range. The
format of these displays is either a single row of up to 80 characters, or two rows of
characters addressed as a single row. The viewing angle ranges from normal to ~ 40° from
normal in the low voltage quadrant, but the precise location of this cone of high contrast
can be varied by adjusting the drive voltage.

To make further progress from this situation there are five main avenues that have
been followed in various laboratories:-

(a)   Restrictions on the optics of the display;
(b)   Improvements in materials for use in established effects;
(c)   Improvements in drive methods for conventional liquid crystal effects;
(d)   Exploitation of new liquid crystal effects whose characteristics are better
      suited to multiplex drive;
(e)   Incorporation of electrical components at the matrix cross-points of display
      cells.

5.2   Displays with Restricted Angle of View

When reduced angle of view is acceptable, or when projection is used, far more complex
displays are possible. One of the most complex was reported by Hitachi (12) where a 120
line TV picture with 160 dots per line and 16 grey levels was demonstrated. The TN effect
was used, and the entire TV receiver and display consumed about 5W from a 15V supply. One

must assume, however, that since 60-way multiplexing was used the angle of view and temperature range of the display must both have been extremely narrow.

Another TV-type demonstration was by Robert (13) who used the variable birefringence effect in a negative nematic material as mentioned in Section 3.6. To satisfy the severe tolerance on cell spacing that this effect incurs, the active cell area was restricted to 6.4mm square. A 10cm square image was then produced by projection. The display consisted of a 128 x 128 dot matrix with 8 grey levels. The response speed at room temperature permitted only 5 images per second, but this rate doubled at 40°C.

5.3   Improved TN Materials

There is considerable commercial pressure for improved materials for multiplexed displays, and it is clear that gradual improvements are continually being made. However, a major breakthrough would be required to improve the threshold sharpness from its present typical value capable of 7-way to 10-way multiplexing to a value that would permit 50-way multiplexing of a reflective TN display. Such a breakthrough seems rather unlikely, so one may only anticipate rather steady progress towards displays of perhaps 4 or 6 lines of alphanumerics from this approach.

5.4   Improved Addressing Waveforms

The Alt and Pleshko optimisation of drive voltages mentioned in Section 5.1 assumed a rather restricted type of waveform where only one voltage ratio was adjustable and where the addressing waveforms depended in a very simple way on the data to be displayed. Several authors (26) have recently considered the potential of completely generalised drive methods. The conclusions of these theories are that, in general, improvements are possible, but these improvements are only significant either when the number of scanned rows is very small or when the number of elements per column which are different from the background is very small. Clearly, neither of these conditions pertains to complex alphanumeric displays, but the application of this type of approach to various special purpose displays is discussed in Section 5.7.

5.5   Alternative Liquid Crystal Effects

Although there are many liquid crystal effects that might eventually be exploited in this way, the two effects mentioned here have been chosen largely because of existing demonstrations of their capability.

The first, known as "two-frequency multiplexing", uses the optics of a conventional TN display, but incorporates nematic materials having unusual dielectric properties. Figure 11 shows the variation of the principal dielectric constants with applied frequency. There is a critical frequency f_c, known as the "cross-over frequency", at which the two values are equal. Below f_c, the parallel dielectric constant exceeds the perpendicular so a low frequency field tends to turn the display on. Above f_c the reverse is true, so
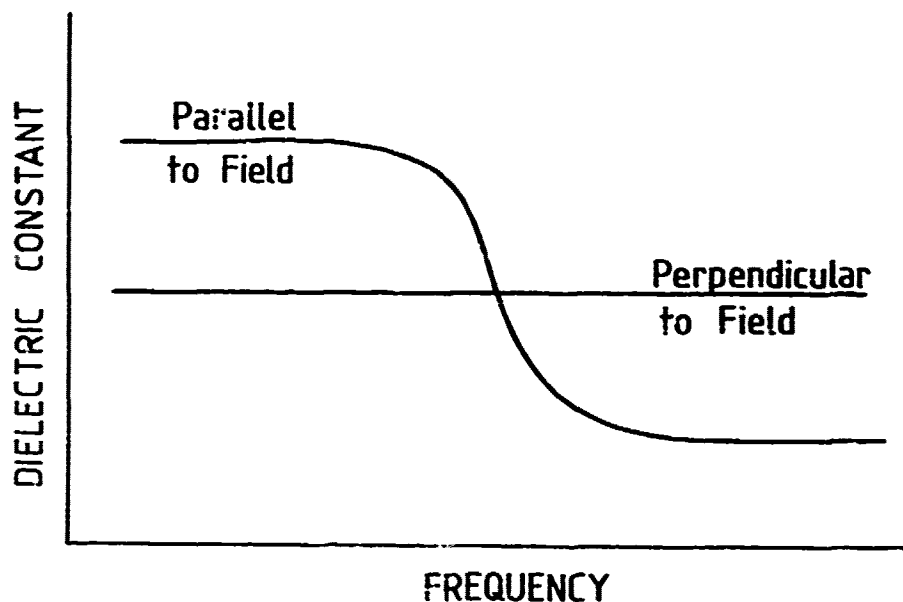
FIGURE 11   "Two-frequency" nematic material; variation of the principal dielectric constants with the frequency of the applied electric field.

a high frequency field tends to turn the display off. A few useful materials exist having f_c in the range 1-10 kHz at room temperature.

This effect has been exploited by van Doorn and de Clerk and by Hosakawa et al(14). both cases high and low frequency drive signals were applied simultaneously. The selection of on and off elements was done via the high frequency signals. The low frequency signal, of constant amplitude, effectively counterbalanced a large part of the effect of the high frequency signals. It can be shown that, provided the ratio of various signal amplitudes is correctly controlled, the number of lines that can be addressed increases proportional t' the applied voltages. The main problem with this method is the variation of f_c with te. .nature; typically f_c doubles with every $8^\circ C$ rise. Consequently, the total temperature range of the method is restricted to maybe 40 degrees by the ran e of practicable drive frequencies. The demonstration of this method by Hosakawa et al(15)used 56-way multiplexing to generate 8 rows of 64 characters. Drive amplitudes were restricted to 40V peak-to-peak, and the temperature range covered was $0^\circ C$ to $40^\circ C$.

The second method, developed by Tani et al (16), exploited the hysteresis and storage effects sometimes found in the characteristics of the cholesteric-nematic phase change effect. Both clear and scattering states were obtained that remained stable for several hours at room temperature, and a method was achieved of switching between these states in a few milliseconds. The largest display consisted of 306 lines of 574 dots at 0.4mm pitch and was driven with ± 14V. The contrast ratio was 24:1 and the angle of view was greater than ± 70°. Unfortunately no information was given on the temperature range of these displays. These are probably the most complex multiplexed LCD yet demonstrated, and may be capable of further development, possibly with incorporation of the pleochroic dyes mentioned in Section 3.5.

5.6   Internal Electrical Components

The advantage of this approach is that it makes only minimal demands on the steepness of the transmission-voltage characteristic of the liquid crystal. The complexity now resides in the cell substrate, where an electrical device, either active or non-linear passive, is placed in series with each liquid crystal element. The electrical characteristic of each device must achieve two objects; firstly, it must block all partial select pulses addressed to other elements; secondly, when a full select pulse occurs it must permit the capacitance of the liquid crystal to charge up rapidly, and when this pulse ends it must prevent the charge leaking away until the next select pulse occurs. Three approaches have been pursued, namely active silicon substrates, thin film transistors on glass, and Varistors.

The Si substrate approach of Lipton et al (17) used a complete 3 inch diameter Si slice as one side of a 1.75 inch square dynamic scattering display. On this substrate was a 175 x 175 arra. of fairly conventional MOSFETs, addressed via an x-y matrix of conductors. A silver reflector was provided for each display dot. The display drive circuits operated at the TV compatible rate of 30 frames per second, but the contrast and gre . scale capability were not disclosed. This approach has considerable potential for further development with the inclusion of decode and drive circuits on the same slice, the use of the DPC effect for better appearance, higher resolution, etc. The chief limitation is that the overall area of the display is restricted to that obtainable from a single Si slice until some reliable method of butting substrates together is developed.

The thin film transistor approach is electrically very similar, in that each display element is addressed via a FET, but it has the great advantage that the substrate is a glass sheet on which all components are vacuum deposited; the size limitation of the Si slice is eliminated. The work of Brody et al (18) was based on a 6" square display with up to 180 x 180 elements. The semiconductor was CdSe, produced in polycrystalline form by vacuum evaporation followed by careful annealing. In this case the TN effect was used, but in principle any other liquid crystal effect could be used. Both alphanumeric and video display modes were demonstrated, the video being refreshed at 60 Hz and achieving 6 shades of grey.

Spear (19) has recently suggested that the characteristics of thin film transistors made of amorphous Si on glass are adequately suited for this application. This material is now readily deposited in thin film form by various methods. Ultimately it may prove to be an easier material to control, requiring simpler processing and producing FETs with more suitable characteristics, but present data is very limited.

The third approach, developed by Castleberry (20), used a slice of the Varistor material, ceramic zinc oxide, as the display substrate. Careful design of the conductor configuration on this substrate ensured that each liquid crystal element was directly in series with a Varistor. The extremely sharp knee in the I-V characteristic of this material was used to discriminate between partial select and full select pulses. A half inch square cell, divided into a 16 x 16 dot matrix, was used to simulate the behaviour of up to a 250 line matrix. The DPC effect was used, producing very good contrast and viewing angle with a black dye mixture. Substrates up to 8" diameter were said to be feasible.

At this stage it is difficult to predict which of these approaches has the greatest potential. Each has the capability of addressing several hundred lines of data, but each also requires considerable technological skill, so the ultimate choice will most probably depend on relative costs and achievable yields.

5.7   Displays with Restricted Information Content

It was noted in Section 5.4 that improved drive methods could be devised for large

matrices provided enough restrictions were placed on the information to be displayed. Two examples of this situation are bargraphs and oscilloscopes.

A digital bargraph display consisting of a single column of dots would normally display data by having all dots below the indicated level on, and all dots above that level off. A liquid crystal display of this type has been described by Kmetz (21) in which the connections between elements were configured to be electrically equivalent to a conventional matrix. This matrix required few external connections and very few distinct drive waveforms. Nevertheless, the 3:1 voltage ratio between on and off elements ensured high contrast viewing over a wide angular and temperature range. Further extension to the multiplexed drive of double and triple bargraphs was demonstrated with only slightly degraded visual appearance.

The oscilloscope scheme of Shanks et al (22) utilised the fact that, when displaying a single-valued function on a matrix display, only one element per column is different from the rest. In practice it is convenient to turn the background elements on and hold the data elements off. The method used a set of different waveforms, one per row, driving the matrix continuously. To obtain an off element at any required row and column intersection it was merely necessary to apply to the column the same waveform as was applied to the row. The pseudorandom binary waveforms chosen here had the advantage that a high, uniform voltage was applied to all on elements giving good contrast and permitting very wide temperature range operation. The entire oscilloscope with 100 x 100 dot display required only 60 integrated circuits and consumed less than 500 mW. It was demonstrated in reflection with both TN and DPC displays, while one model used a transmissive TN display for large scale projection.

5.8 Light Valve Projection Displays

The two examples chosen here are notable for the fact that they use effects that are not exploited elsewhere.

The first, described by Hong et al (23), was the result of many years of development at Hughes Aircraft Company. The system contained a CRT which acted as a primary image generator and which was optically coupled to a liquid crystal cell either by fibre optics or by a lens system. The complex liquid crystal cell included a photoconductive layer on which this data was imaged and which controlled the spatial distribution of voltage across the liquid crystal. The liquid crystal effect used was a hybrid between the TN and the variable birefringence effects. Polarised projection light was incident on the opposite face of the cell, and was isolated from the photoconductor by a dielectric reflector and a light blocking layer. Different wavelengths in the projection light were reflected, according to the state of the liquid crystal. The projected image then consisted of data in one colour on a background of another colour, the colours being partially selectable by the operator. The system, which was portable, was capable of producing high contrast images with up to 700 line resolution, but no grey scale.

An earlier laboratory demonstration (24) using a different liquid crystal effect gave a multi-colour information display with a simultaneous black-grey-white capability. Unfortunately, the stability of the liquid crystals used for this very versatile effect was not adequate for commercial exploitation.

The second approach, developed by Melchoir et al (25), Dewey et al, and others, is the only display device discussed here that uses smectic liquid crystals. This smectic material can exist indefinitely in either a transparent, homeotropic aligned, state or a scattering state. The state may be controlled locally, with resolution of a few tens of microns, by laser heating either with or without an electric field. In this way data may be written into the liquid crystal cell, stored, and if necessary erased or up-dated. The cell can act simultaneously as the transparency in a simple Schlieren projection system, permitting real-time storage and display of dynamic data. Several variants of the scheme have been made, some used in transmission, others in reflection, with various writing lasers. One of the most complex was capable of completely rewriting the 1500 x 1500 resolution elements in 3 seconds.

6. CONCLUSION

In this brief review an attempt has been made to provide sufficient background knowledge of liquid crystals for the display user to understand the physical basis of the effects used to display information. Some of the capabilities and limitations of currently available displays have been detailed, together with information on a wide selection of laboratory prototypes and techniques which may eventually be used in more complex, and possibly more specialised, applications. It is clear that progress has been rapid and many possibilities are now available for further exploitation. Although a high resolution, television type, display is still a long way off, prospects are very good for development in the near future of displays having high information content, wider temperature range, higher speed at low temperatures, better visual appearance and improved environmental tolerance.

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CATHODE RAY TUBES AND PLASMA PANELS AS DISPLAY DEVICES FOR AIRCRAFT DISPLAYS

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SUMMARY

The various types of electronic display presently being incorporated in aircraft and the displays being proposed for future use are reviewed and their technical requirements examined. These include head-up displays, helmet mounted displays and various head-down displays which can be generated by TV techniques. The state of the art of CRT and d.c. plasma technology is described and the suitability of these two devices for the different displays is discussed, along with possible future improvements in performance.

INTRODUCTION

The use of electronic displays in aircraft has increased steadily over the last few years and shows signs of increasing more rapidly in the future. Apart from weather radar, the displays have up to now been virtually confined to military aircraft but the next generation of commercial aircraft will almost certainly have several electronic displays. These are likely to include a vertical situation display, horizontal situation display, attitude direction display, fuel and engine management display and perhaps a head-up display.

In future military aircraft additional displays are also required for FLIR, radar and weapon TV and for moving map. Because of the limited space available in the cockpit the trend is towards multi-function displays. Even so, several displays per aircraft would still be necessary to cope with all the requirements. The British Aerospace advanced cockpit design incorporates seven CRT displays, which with about 10 other instruments, replace more than 100 conventional instruments.

All of these displays, by definition need some form of display device. Up to now the device that has been exclusively used is the CRT and most of the new displays presently in development also incorporate the CRT. The CRT is, however, a rather bulky device and because of this there has for many years been a search for a flat panel replacement. One possible candidate for this task is the gas discharge or plasma panel.

The purpose of this article is to look at how present-day CRT's and plasma panels meet the requirements for the display device in aircraft electronic displays and to briefly discuss the improvements that could be expected in the near future.

DISPLAY REQUIREMENTS

Before the suitability of the CRT or plasma panel for aircraft displays can be discussed it is necessary to know the requirements of the various displays.

The different types of display may first of all usefully be divided into two main categories, namely those that have to be viewed in the "open" cockpit of a high performance military aircraft and those that may operate in the back seat of military aircraft or in the cockpit of civil aircraft where at least some shielding of the display from external illumination may be achieved. The basic difference in these two sets of applications is the level of external illumination which may fall upon the display. In the former case where there is unshielded sunlight or sunlight reflected from white clouds the illumination is extremely high and is usually quoted as 10,000 ft.cd.

In civil airline cockpits it may be possible to impose a limit of perhaps 3,000 ft. cd., a significant reduction, whereas in other areas the illumination may be controlled to any desirable level. Thus for use in "open" cockpits the display brightness must be as high as possible. This also applies to a head-up display which has to be viewed against this high external illumination as a background.

In all other characteristics, the requirements for displays whether in the open cockpit or not are similar. Generally accepted requirements for some typical displays are summarised in Fig. 1.

Three of the displays will be looked at in a little more detail, the head-up display, an extension of the head-up display - the helmet mounted display, and the TV display which as far as device requirements are concerned is quite similar to all other displays such as the EADI, HSD, FLIR, Engine Management etc.

Display Parameter	Head-Up	EADI	HSD	FLIR	Navigation and Fuel Management	Tactical Display	Raw Radar	Helmet-Mounted
Brightness Civil	Viewable against 10,000 ft.L. background brightness	Viewable under 3,000 ft.cd. ambient illumination	Viewable under 3,000 ft.cd. ambient illumination	-	Viewable under 3,000 ft.cd. ambient illumination	-	-	-
Military	"	Viewable under 10,000 ft.cd. illumination	Viewable under 10,000 ft.cd. illumination	Viewable under 10,000 ft.cd. illumination	Viewable under 10,000 ft.cd. illumination	Viewable under 10,000 ft.cd. illumination	Viewable under 10,000 ft.cd. illumination	Viewable against 10,000 ft.L background
Writing Mode	Stroke	Raster	Raster/ Stroke	Raster	Raster	Raster (Scan converted) Radar	B. Scan	Raster
Contrast	2:1 against highest background	2:1 against highest background	2:1 against highest background	2:1 against highest background	2:1 against highest background	2:1 against highest background	2:1 against highest background	2:1 against highest background
Resolution	Trace width approx. 0.010"	800 TV lines	800 TV lines	800 TV lines	800 TV lines	800 TV lines	Trace width approx. 0.020"	800 TV lines
Dynamic Range	1 level	7 grey shades	1 level	7 grey shades	4 grey shades	2 grey shades	1 level	7 grey shades
Size	Device should be as small as possible	5" to 9"	5" to 9"	5" to 9"	5" to 9"	5" to 9"	5" to 9"	Device should be as small as possible

Fig. 1.   Summary of Typical Display Requirements

HEAD-UP DISPLAY[1]

In this type of display the internally-generated image is projected at infinity and superimposed upon the real world view of the observer.   For two main reasons this technique imposes tremendous requirements on the brightness of the device on which the internally-generated image is produced.   Firstly, the image is superimposed upon the real world and hence must be bright enough to be visible against this background brightness.   Secondly the conventional optical elements which collimate the image and combine it with the real world view have losses such that only somewhere between 15% and 20% of the light produced by the image source is usefully used.

Using some approximate figures;   if a projected image brightness of around 1,800 ft.L is necessary for adequate visibility, then the source brightness has to be a minimum of 9,000 ft.L and up to around 14,000 ft.L.

HELMET-MOUNTED DISPLAY[2]

This type of display is an extension of the head-up display which removes the restriction of the fixed viewing aperture having a relatively narrow field of view, of the conventional head-up display.   In this case the display moves with the observer's head movement.   Whilst the basic electro-optical requirements of the helmet-mounted display are similar to those of the head-up display there is one other requirement of overriding importance and this is the weight of the display.   Any increase in the weight of the helmet is undesirable but it is especially so in high-performance aircraft where the effective weight may be increased several fold due to 'g' forces in high-speed manoeuvres.

TV RASTER-FORMAT DISPLAYS

Almost all of the other displays presently used or envisaged are of this type, although they may be displaying the output from different sensors such as low light television, forward-looking infra-red or scan-converted radar and may also have an alpha-numeric content or other symbology.

Brightness is specified as being sufficient for the display to be viewable under a particular value of illumination, rather than being specified as a particular value of brightness since it is possible to trade-off brightness and contrast and grey shades to produce optimum performance by the use of optical filters.   The brightness of the display is reduced by filters but the background brightness due to reflected ambient illumination is reduced even more such that the contrast is enhanced.

THE CATHODE RAY TUBE[3]

Since the CRT is getting on towards 100 years old and is universally used as the display device in television receivers and oscilloscopes, most people are familiar with its construction and mode of operation.

Basically the CRT consists of an evacuated envelope, usually of glass, with a source of electrons at one end and a luminescent screen at the other.   Means of modulating the source of electrons and of focusing and deflecting it, are incorporated within the envelope or are provided by external components closely associated with the envelope.   A schematic representation of the CRT is shown in Fig. 2.

ADVANTAGES

The CRT has two very important characteristics which presently give it an advantage over all other display devices. The first of these is the ease with which the electron beam can be deflected and hence how readily the single spot can be made to produce any kind of display. The second important characteristic, which has many facets, is the extreme versatility of the device. The CRT can readily be made into a variety of shapes and sizes by the provision of a suitable envelope. The present limits (not the ultimate) in size are from around ½" diameter up to 36" diameter and the screen shape usually varies from circular to rectangular with different aspect ratios.

By using different phosphors to form the luminescent screen the CRT may also be made to produce a display with widely different colours and persistence.
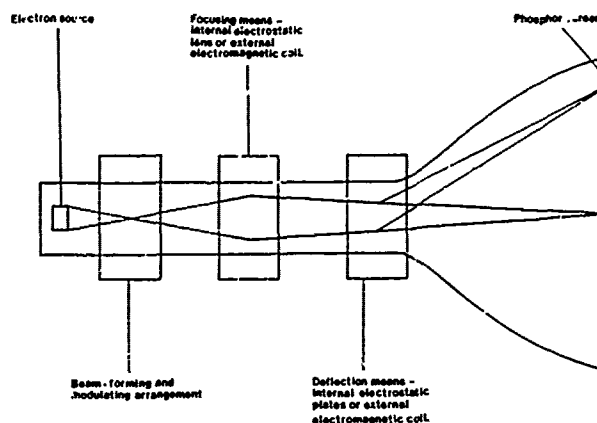
Fig. 2. Schematic Representation of CRT

TRADE-OFF'S IN DESIGN

Another aspect of the CRT's versatility is the fact that trade-off's may be made between a number of the important characteristics. For example, a trade-off may be effected between the resolution and the light output obtainable. Resolution and tube length may be traded, as may deflection power and length. Similarly a trade-off situation exists between brightness and writing speed.

In general, the following practical considerations apply:-

1. The higher the light output required the lower is the resolution.

2. The shorter the tube, the greater is the deflection power required.

3. The shorter the tube, the greater is the difference between the resolution at the centre of the display and at the edge of the display.

4. The shorter the tube, the lower is the resolution.

5. The slower the writing speed, the brighter is the trace.

These are, however, only generalities. Because the principle of scaling applies, a tube of only 4 inches in length (but only 1" diameter) can in fact be manufactured to produce a display of 800 lines resolution.

Because of the various trade-offs and interrelation of the different properties the design of a CRT may be optimised for a particular application such that a very large number of widely differing display applications may be satisfied by the CRT.

FUTURE IMPROVEMENTS

There are two fundamental electron optical limits to the performance of the CRT. The first of these is the so-called Langmuir limit[4] which states that the maximum current density which can be achieved in the image (spot) is limited by the velocity distribution of the electron beam and that the current density in the image is directly proportional to the current density from the cathode. This in practical terms puts the limitation onto the current density that can be achieved from the cathode with acceptable life. Thus one possible area for improvement is the development of cathodes capable of operating at increased current density. There is some scope here insofar as the present CRT's almost all use the oxide cathode whilst it is known that a dispenser cathode[5] will operate at a higher current density. Incorporation of dispenser cathodes will therefore produce improved performance.

The second fundamental limit is the limit due to space charge[6], which limits the beam size into which a particular value of electron current may be constrained.

Further practical electron-optical limits are those imposed by aberrations[7,8] in focusing lenses and deflection arrangements. An associated limitation is the conversion efficiency and life of the phosphors used in the luminescent screen of the CRT. Thus reductions in lens aberrations and improved phosphors permit of further improvements in CRT performance.

THE CRT IN HEAD-UP DISPLAYS

The CRT is the only device currently used in head-up displays and meets the requirements quite well except for brightness where the performance is marginal.

It is necessary for the trace brightness to be a minimum of 10,000 ft.L and this can be achieved but only by using a "slow" writing speed. Slow that is, compared to TV writing speeds, since the brightness is achieved with a speed of 1,000 inches per second (with a 50 Hz refresh rate).

Present-day HDU's have a somewhat limited field of view and to increase this, without increasing the transmission efficiency of the optical system, entails an increase in the already marginal brightness. (It is possible, however, to increase the transmission efficiency of the optical system by using diffraction or holographic optics[10].) More accurately, an increased field of view requires the same brightness at an increased writing speed. This can in fact be achieved by increasing the beam current and/or increasing the CRT anode voltage.

Increasing the beam current would impair the resolution somewhat (unless a dispenser cathode were used) and would also decrease the screen life unless a more rugged phosphor were used or a quartz or sapphire faceplate were used to increase the heat dissipation from the phosphor.

Increased anode voltage entails increased deflection power and a more expensive and possibly less reliable high voltage supply. Nevertheless, at present no other alternative is available, although development work is being carried out on passive devices such as liquid crystal displays[11].

A head-up CRT and package is shown in Fig. 3.
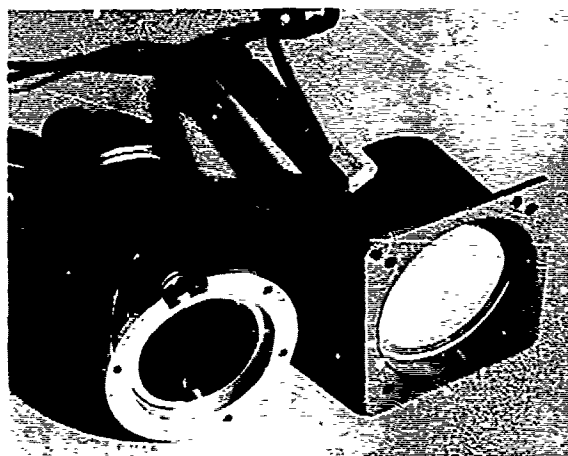
Fig. 3. Head-up CRT and Package
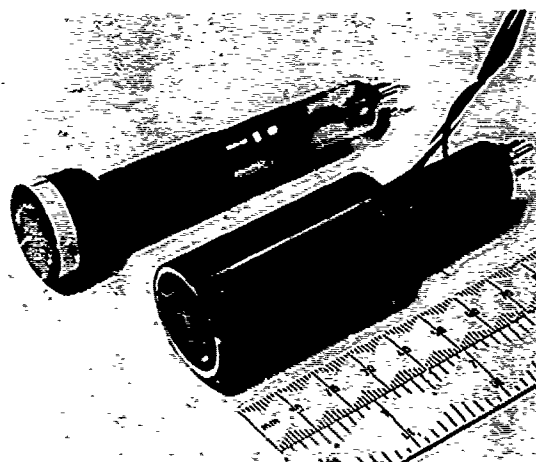
Fig. 4. Helmet-mounted CRT and Package

THE CRT IN HELMET-MOUNTED DISPLAYS[12]

The CRT may be scaled down in size, keeping virtually the same electron-optical performance. The practical limit at present is a device about 1" in diameter and 4" long with a weight of 80 g to 90 g - just about 3 ozs. This is for a package including means for deflection, high voltage insulation, magnetic shielding and means of mechanically incorporating the device in an optical system. Such a device is shown in Fig. 4.

The brightness is not completely adequate but this is because the conditions of operation are different. The conventional head-up display usually just displays symbology whereas the helmet-mounted display usually consists of a raster display, entailing higher writing speed. Also, the permitted anode voltage is not as high for the helmet-mounted display as for the head-up display.

It would appear that the CRT may never be a completely satisfactory and fully acceptable device for a helmet-mounted display but once again it is the only device at present which will allow a system to be produced for limited application. Flat panel devices, offering low weight and low power consumption have problems of addressing and do not as yet have the necessary resolution.

THE CRT IN TV RASTER FORMAT DISPLAYS

CRT's of suitable size for cockpit displays, say 7" x 5" rectangular format can be produced which will display a raster of 800 lines resolution at a luminance of around 2,000 ft.L. By the use of suitable optical filters, the display will substantially exhibit 7 shades of grey under the specified 10,000 ft.cd. ambient illumination.

The best performance is obtained using a narrow-band emitting phosphor such as P43 in conjunction with a matching narrow band-pass filter, with external anti-reflection coating[13].

The phosphor emission characteristics and the filter transmission characteristics are depicted in Fig. 5 and a complete package suitable for a head-down TV format display is shown in Fig. 6. The actual transmission of the filter to the phosphor peak wavelength is approx. 15%, whilst the transmission to normal daylight is less than 1%.
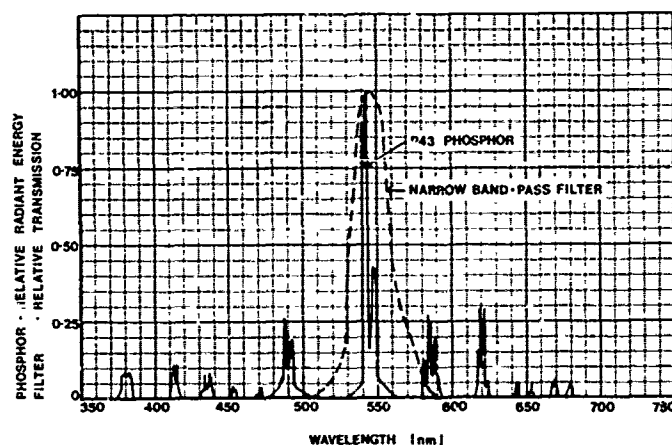
Fig. 5. Characteristics of Narrow-Band Phosphor and Matching Contrast Enhancement Filter
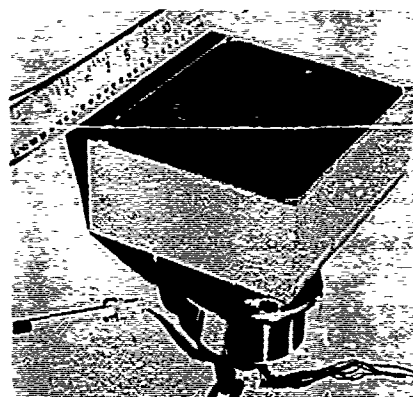
Fig. 6. Head-Down CRT Package

POSSIBLE CRT REPLACEMENT TECHNOLOGIES[14]

A suitable replacement for the CRT has been sought for the last 20 years or more and during the last few years several technologies have received considerable attention. These include electroluminescent panels, light-emitting diodes, plasma panels, liquid crystal displays, electrochromic and electrophoretic displays and others. Very many papers have been published on the individual technologies and several review papers have been written.

At the present time, however, the only one of these possible contenders that can provide a competitive display (including cost, not just performance) of a reasonable number of characters, say 100+, in the aircraft cockpit environment, is the plasma panel. Even so, this is limited in the applications for which it may be used; it is not, for example, capable of displaying a TV raster format at the required level of brightness.

There are two kinds of plasma panel, one a.c.[15] operated and the other d.c.[16] operated. Now, the a.c. panel can in fact display a TV picture, although special techniques have to be employed to provide a grey scale, but it is not sufficiently bright for aircraft applications. The d.c. operated panel has the necessary brightness but does not have the resolution for TV pictures. It is used therefore in applications where alphanumeric information alone is adequate as in Area Navigation or Engine Control Displays.

d.c. PLASMA PANEL

CONSTRUCTION

The d.c. plasma panel is a flat panel containing an array of small, discrete gas discharge cells.

It consists of a sealed sandwich of three glass plates, one carrying cathodes and their connectors, one with a matrix of holes to define the individual discharge cells and the third carrying anodes, series resistors and connectors.

The connectors are arranged so as to produce an X-Y matrix of rows and columns of cells. The construction is illustrated in Fig. 7.

PRINCIPLE OF OPERATION

A d.c. maintaining voltage is applied to the whole panel and pulses are fed to particular anode and cathode lines. Where anode and cathode pulses of the correct magnitude reinforce each other at an intersection, the voltage is sufficient to strike a discharge within the individual cell at the intersection. After the pulse is removed, the cell is still kept alight by the maintaining voltage. This arises from a property of an electric discharge in a gas whereby a certain

Fig. 7. Construction of d.c. Plasma Panel

voltage, whilst insufficient to strike a discharge may be sufficient to maintain the discharge once it has been ignited by a sufficiently high strike voltage. The value of the discharge current is set and limited by the value of the resistor in series with the cell. This property provides inherent memory, since once a cell is lit a positive erase action is required to switch it off. Erasure is performed by reversing the polarity of the pulses so that the voltage at the intersection reduces to a value which is insufficient to maintain the discharge.

Due to the memory property the duty cycle is effectively 100% so that maximum brightness and flicker-free operation is obtained. A variety of gases may be used, each giving its own characteristic discharge in terms of colour and operational voltages. The gas most frequently used is neon or a mixture of neon and argon, giving the familiar orange discharge. By coating the walls of the cells with a phosphor a larger gamut of colours may be produced since the phosphor is excited by the UV content of the discharge and by electrons and ions in the plasma.

ADDRESSING AND DRIVING

Like all other flat panel technologies but unlike the CRT the plasma panel consists of a large number of discrete picture elements or pixels as they are known, in this case small gas discharge cells. To produce a TV picture of only 500 lines with equal horizontal and vertical resolution requires a quarter of a million pixels. To produce a display of only 100 alphanumeric characters, with each character formed by a 7 x 5 cell matrix, still requires 3,500 active pixels. To address each one of these pixels separately requires an impracticably large number of connections. Thus flat panel displays usually use some form of matrix addressing where the individual pixels are connected into orthogonal rows and columns. This reduces the number of connections in the case of the TV example to 1,000 and in the alphanumeric example to 120.

Having reduced the number of connections, there is still the problem of providing a satisfactory luminance. In the TV example again, if each pixel is addressed sequentially, each pixel can only be switched on for one quarter of a millionth of the frame duration. This means that the average luminance is very low, being equal to the peak luminance from an individual pixel multiplied by the duty cycle, which is the time each individual pixel is addressed, divided by the frame duration. This is basically no different from the CRT situation where only one element of the luminescent screen, equal to the electron beam spot size, is addressed at a time, but the CRT can have an extremely high instantaneous peak luminance. The CRT is also helped bu the fact that the pixel is not switched off immediately after the beam passes but continues to emit due to the persistence of the phosphor.

If the panel is addressed one line at a time rather than one pixel at a time the duty cycle is effectively increased; by 500 times in the TV example quoted, hence producing a higher average luminance. For this reason this is how most matrix panels are addressed. A further increase in luminance is possible if the pixel has the equivalent of phosphor persistence and the maximum possible luminance is achieved if it has memory such that it stays switched on for the whole time between successive frames. The d.c. plasma panel does have memory and hence may be operated at relatively high luminance. The panel could be operated at as high a luminance as a CRT but at the current density required to do this, there is excessive sputtering of the cathode material and the life of the panel is significantly reduced.

Using line-at-a-time (row or column) addressing, grey-scale (dimmable display) may be obtained by varying the time between turning on a line and subsequently erasing it.

In this case, one is in effect not fully using the memory property and hence the whole sequence has to be repeated at a refresh rate sufficient to eliminate flicker. Elimination of flicker at reduced refresh rates is also helped, as in the case of the CRT, by the persistence of the phosphor if one is incorporated.

FUTURE IMPROVEMENTS

Improvements in resolution, light output and contrast are possible so that the d.c. plasma panel should be capable of being viewed satisfactorily under the highest ambient illumination and whilst the resolution is unlikely to be sufficient for TV applications it should be possible to present vector and graphic information in addition to alphanumeric.

THE d.c. PLASMA PANEL IN AIRCRAFT ALPHANUMERIC DISPLAY

The plasma panel is not bright enough to be used as the image source for a head-up display nor can it be made small enough for a helmet-mounted display.

It does provide an attractive display device for a purely alphanumeric display which may be used for Area Navigation, Fuel Management etc. The plasma panel overcomes some of the disadvantages of the CRT. Being a flat panel it does not have the bulk of the CRT and with its driving circuitry it occupies less volume than a CRT with the same display area, with its associated driving circuitry. The plasma panel does not require the very high voltage supply necessary with the CRT. The characters of the display being formed from discrete cells, have a distinct, highly legible appearance and of course, maintain accurate positional registration.

The gas discharge may be arranged to have a significant U-V content so that it will excite a phosphor within the cell. Narrow-band emitting phosphors are currently not very efficient under plasma panel excitation conditions but some contrast enhancement with filters as in the CRT, is possible using the green P1 phosphor.

The plasma panel is an intrinsically rugged device, comparable to the specially ruggedised CRT's developed for adverse environments and it is less susceptible than the CRT to the effects of stray magnetic fields.

A display can be made which is legible under illumination conditions encountered in civil aircraft cockpits. Examples of such display devices are depicted in Fig. 8 and a packaged version including drive electronics is shown in Fig. 9.
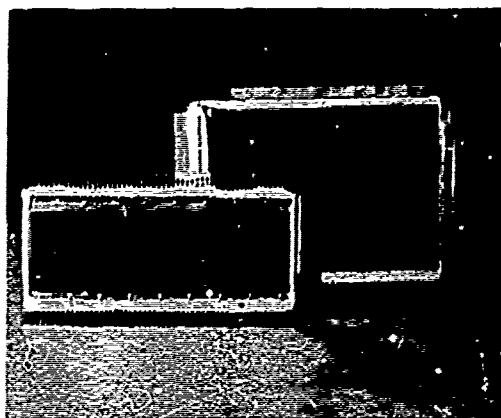
Fig. 8. Typical d.c. Plasma Panel
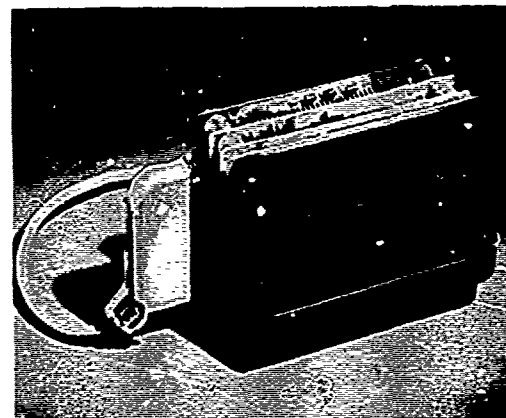
Fig. 9. Plasma Panel Display Package

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ACKNOWLEDGEMENTS

LARGE AREA GAS DISCHARGE DISPLAYS
by
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A gas discharge has several properties which are particularly appropriate for display. A neon discharge, for example, emits sufficient light for an attractive display with an efficiency of about 0,5 lm/W, or appropriately chosen gases emit ultra-violet radiation than can be used to excite phosphors as they do in fluorescent lights. The gas discharge is characterized by an ignition voltage above which an avalanche phenomenon takes place between the exciting electrodes and establishes the discharge with simultaneous heavy emission of photons. This threshold potential is of primary importance when the display should consist of a matrix of cells. There is also an extinction voltage below which no discharge can be maintained.

Therefore, since between the ignition and extinction voltages the cell can be either "on" or "off", depending upon the previous conditions, it is a bistable element.

Gas discharge displays or plasma displays are generally classed as a.c. displays and d.c. displays. In d.c. displays the electrodes or resistive extension of these are immersed in the gas (ac operation would be possible but almost always discharge currents are unidirectional). In a.c. display a dielectric surface isolates the electrodes from the gas with which they only have an electrostatic coupling and only a.c. operation is possible. Both can be operated in a storage or non storage mode (storage meaning that the memory is inherent to the display device, whereas in the non-storage or cyclic mode the memory is external to the display and the image information is transfered to the display device sequentially and refreshed frequently enough to avoid flicker).

A.C. PLASMA DISPLAYS

Description

Fig. 1 shows a cutaway view and a magnified cross-section of a large area a.c. plasma panel intended to display a great number of characteres or elaborated graphics. It consists of two identical glass plates (1) imprisoning a gas (2) in which the discharge takes place. The inside surface of each glass plate carries rows of parallel conducting electrodes (3) insulated from the gas by a dielectric layer (4) which is to be made of materials satisfying specific requirements such as resistance to sputtering by ionic bombardment, lowering the firing voltage etc... the plates are assembled with their electrode networks at a 90° angle to each other and with a small uniform gap between them. In some products a matrix of holes in a thin plate locates the cells but in most products the cells just correspond to the intersections of the two sets of crossed rows of electrodes. The gap is first evacuated and then generally filled with a neon-argon mixture where a red-orange luminescence occurs with each electrical discharge.

Operating principle

In operation, an a.c. voltage called the sustaining voltage is permanently applied to all X and Y electrodes. Its value is such that the electric field is insufficient to cause discharge of the gas. In the absence of any other signal, the panel is in the "off" condition.

Each point of the panel corresponding to the crossing of a line and a column can be addres-

.../...

* This contribution was prepared as a note to the editor in order to stress some important features of display devices similar to those described in the previous paper.

sed by applying a writing signal in the form of an auxiliary instantaneous voltage exceeding the firing voltage which initiates the discharge.

The ions and electrons generated by this discharge will build up on the dielectric covering the electrodes creating an opposite potential ($-V_M$), the actual potential across the gas will drop causing the discharge to be rapidly quenched. During the next half-cycle, when the substaing voltage presents a reversed polarity, the potential of the wall has no longer an adverse effect but on the contrary will add to the sustaining voltage so that the resulting voltage is sufficient to exceed the firing potential. A new discharge will occur with corresponding electron and ion deposit then extinction ; the addressed point will continue to fire once per half-cycle of the sustaining voltage.

As a conclusion, the Plasma Display Panel provides a form of bistable memory ; the sustaining voltage keeps a "non-written" point in the "off" state and a "written" point in the "on" state (initiated by a short pulse of the right phase which has momentarily increased the applied voltage). Figure 2 illustrates such a process.

In order to erase a selected written point, an appropriate short pulse voltage is applied to the corresponding pair of X and Y electrodes which cancel the stored charges and hence the corresponding potential.

Characteristics

. The information is displayed in the form of luminous dots at the crossing points of two sets of conductors : X (lines) and Y (columns).
. Each of these dots can only remain either in the "on" state or in the "off" state thus providing an inherent bistable device.
. The written information is stored without any need of "refreshing".
. In most cases, the display appears in orange color which corresponds to the emission spectrum of ionized neon gas (620 nm).
. The display surface is perfectly flat, and thin.
. No high voltage, no X ray emission.
. Very long operating life.
. Rugged construction.
. Transparent panel possible allowing rear projection or image superposition.

System interface

The voltages to be applied to the electrodes are of the order of 120 V. at a frequency of about 50 kHz. The operating principles described above are in fact greatly simplified, the actual operation process being much more complex. Therefore to make the display panels readily available to the users to achieve a "display function", most manufacturers provide them with factory-set drive electronics which can be made very compact and fully environmentalized for adverse conditions.

The address circuits of most alpha-numeric or graphic panels employ multiplexing technology, a network of two diodes and a resistor being associated with each electrode plus high voltage driving amplifiers. This is at present made with discrete components in association with integrated diodes and resistors networks resulting in high cost.

A.C. plasma is one of the two most difficult interface I.C. problems (the other one being

a.c. electroluminescence with which there are similarities). The difficulty of integrating stems from the high voltages involved (100 to 170 V or even more for some driving schemes) and to a lesser extent from fast switching (50 kHz) requirements, driving capacitive loads with large surge currents and "totem pole" output etc... 32 channel 40 leads IC drivers for plasma panels have been announced, but prices still remain unfavourable due to their complex manufacturing process which implies several different IC technologies. However, EPI-FET and D. MOS approaches appear to be very promising solutions and work is underway in several countries.

For instance, apart from the power supply a typical alpha-numeric panel will only require the following TTL signals :

- "line" and "column" addresses of the character.
- ASCII code of the character.
- Control signals : "writing", "selective erasure", or "total erasure".

Graphic panels of course require some more inputs.
From the secrecy point of view due to their inherent acyclic type of operation these panels compare very favourable with other display media where the information is periodicaly refreshed or delivered through a fixed scheme and may thus be easily deciphered.

ERGONOMIC FACTORS

. The display is absolutely flicker-free due to the very high supply frequency and the pattern displayed is steady, thus avoiding any fatigue of the operator even after a long time.

. No image break-up in case of relative motion between the absence and the display, unlike with some other types of "refreshed" displays.
The viewing angle is wide (180° and even 360°)

. The luminance of the display is perfectly uniform (no vignetting) and high ($200_{cd}.\, m^{-2}$). It may be varied. Contrast is good and color is agreable.
. The display is inherently free of geometrical distorsion.
. The resolution is already high (0,4 mm cell pitch or 60 lines/inch) and may still improved.
. Other colors are possible.

STATE OF THE ART

A.C. plasma display technology is currently a mature one being manufactured by a dozen companies in the USA, Japan and Europe. It is indeed the only technology for large area flat displays to have reached such a point after 15 years of continuous development. Panels with display capability ranging from about 200 characters (16000 pixels) to 21000 characters (1024 x 1024 pixels) with resolutions from 0,8 to 0,3 mm (i.e. 32 to 83 lines/inch) and useful areas from 10 x 10 cm to 45 x 45 cm are available, some with full graphic capability and in assemblies allowing rear projection or through-viewing. They have already found numerous civil (like the PLATO teaching system, or banking terminals) as well as military applications (like the MIFASS project - Marine Integrated Fire and Air Support System - where a large, high resolution, transparent display is requested).

Resolution

The 512 x 512 pixels with a resolution of 0,4 mm is today the workhorse of most displays and is manu-
factured in large quantities. For a two time increase in resolution, linear cell dimensions would
have to be reduced by a factor of two and the gas pressure increased by the same amount. This value
of gas pressure becomes a problem since it is above atmospheric pressure and the panel "inflates"
making the gap between the plates less uniform. Thus high resolution leads to some difficulties
with voltage operating margins which require drive waveforms optimization or materials or processing
modification or adjustment.

Color

Multicolor a.c. plasma displays have been investigated where stripes of phosphors of different colors
were deposited on the plates. One of these phosphors was excited by the UV radiation emitted by
Xenon of the adjacent cell, but UV optical cross talk was a problem. Other attemps have been
reported but no production of color panels is known at present. However, the development of such
panels remains possible, provided enough interest is expressed.

Image

The a.c. plasma device, yields two bistable levels of luminance for a single cell operated with a single-
frequency, single amplitude continuous sustain waveform. Several approaches can lead to multilevel
of luminance e.g. by modulating the length of time a given cell is in the "on" state.

Drive electronic

As already mentioned the limiting factor for a very wide use of a.c. plasma panels is the present lack
of high voltage integrated drive-electronics components. Once this barrier is crossed, design and
assembly of the drive electronics will be greatly simplified and prices could drop very significantly.

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1 GLASS PLATES

2 GAS

3 ELECTRODES

4 DIELECTRIC

5 SEAL

CUT-AWAY VIEW

CROSS SECTIONAL VIEW
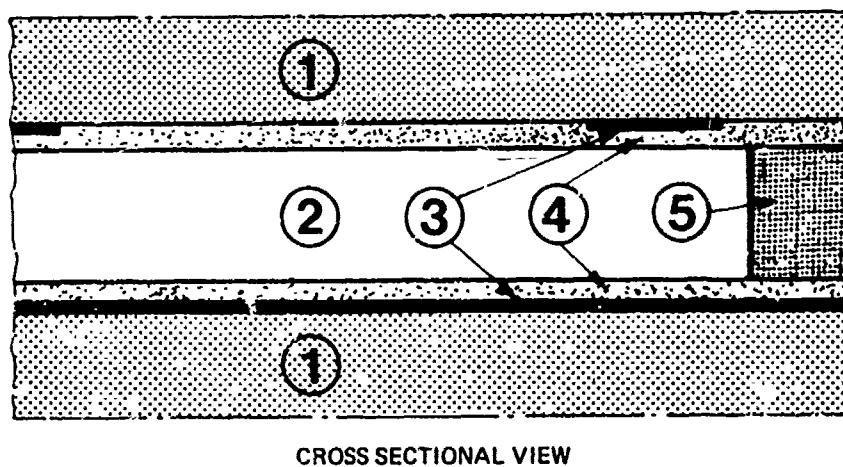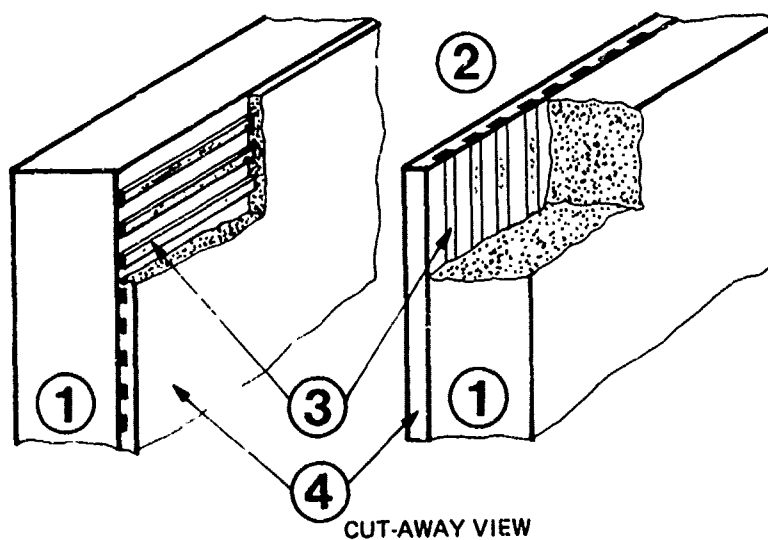
Figure 1 - PLASMA PANEL
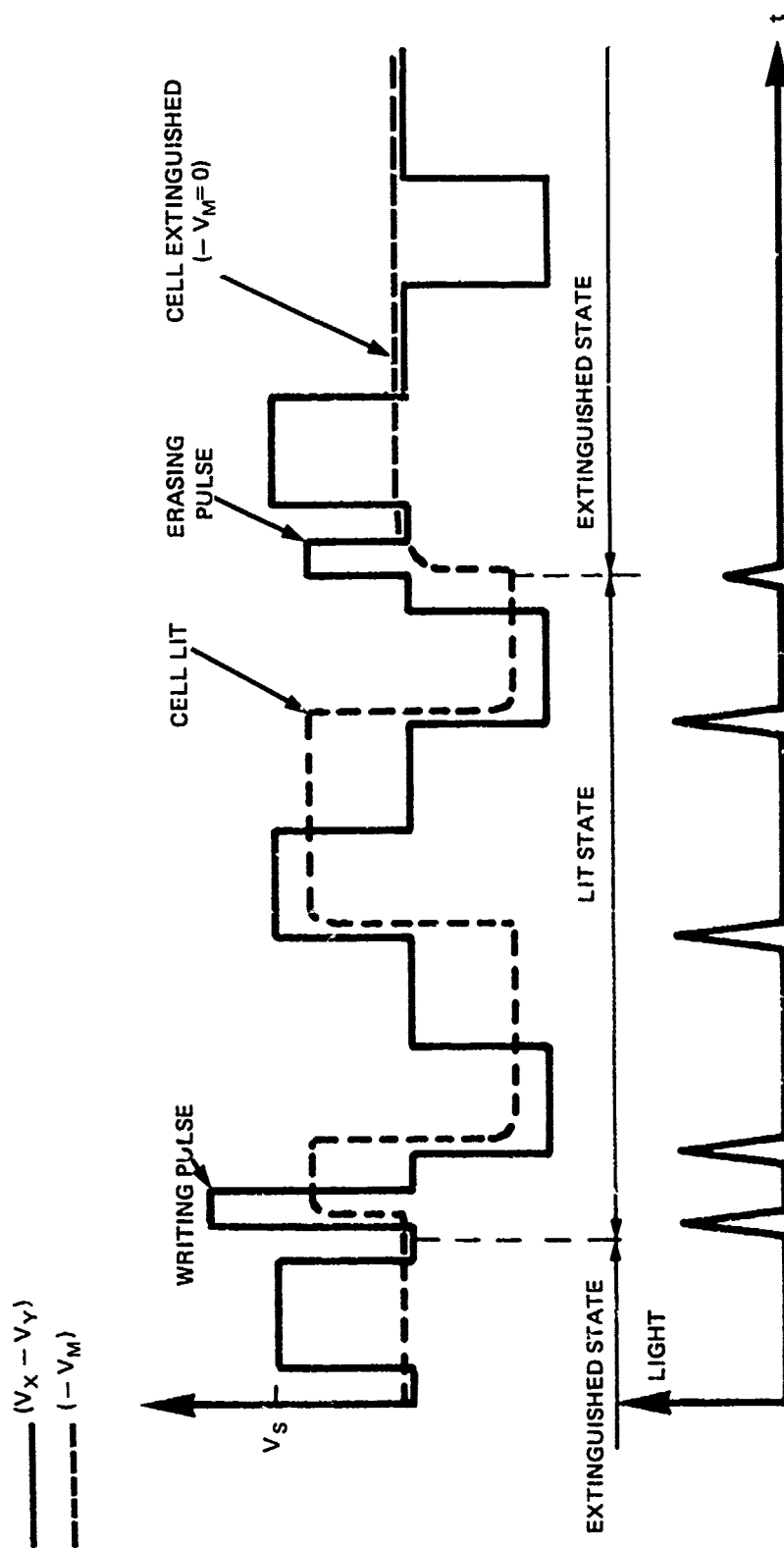
Figure 2 - STORAGE, WRITING, AND ERASING

OPTICAL INFINITY LENS DEVELOPMENTS
FOR FLIGHT SIMULATOR VISUAL DISPLAYS

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SUMMARY

A very fast, large aperture magnifying optical package which can present to the observer a displayed image at optical infinity has been developed. The PANCAKE WINDOW™*, so called because of its minimal depth and relatively flat appearance is currently being used in two Air Force flight simulator visual displays. The optical quality of this magnifier is due to the fact that it is comprised of reflective, and not refractive elements. The advantages of its configuration as an on-axis reflective system and the optical properties of its elements are presented. The latest improvement to its development, incorporation of a spherical holographic beamsplitter mirror, is discussed. This development holds promise for reducing both the cost and weight of the package. A technique for reducing unwanted optical effects by tilting the birefringent package of the window is also discussed.

1. INTRODUCTION

In the early 1970's two U.S. Air Force flight simulator programs were in progress which incorporated visual displays comprised of in-line infinity optical packages called PANCAKE WINDOWS™. When coupled with a high brightness, high resolution cathode ray tube (CRT), the WINDOW /CRT unit offered a compact, efficient visual display. When mosaicked with other units, on a dodecahedron structure, this optics/CRT combination offered the capability to provide a wide field-of-view visual display for the pilot observer. The Advanced Simulator for Pilot Training (ASPT), developed by the Air Force Human Resources Laboratory, has a seven channel visual display with a wrap-around field-of-view of +150° horizontally and +110° and -40° vertically. Of all the various visual simulation techniques investigated for the ASPT program, only the mosaicked in-line infinity display had the capability for fulfilling the majority of the visual simulation requirements. The Simulator for Air-to-Air Combat uses eight faces of a dodecahedron. Both of these simulators supply a partial sphere of vision nearly equal to the partial sphere of vision enjoyed by the actual aircraft they simulate. The fields-of-view are contiguous and even provide overlap fields between windows to allow for substantial head motion of the pilot. Both systems are monochromatic because the CRTs are monochrome; the classical PANCAKE WINDOW™ is capable of operation across the whole of the color spectrum.

2. CLASSICAL PANCAKE WINDOW™

The classical PANCAKE WINDOW™ has proven to be very successful as an infinity display system in many applications where performance and cost are important. The typical PANCAKE WINDOW™ provides the following characteristics:

a. 37 inches of eye relief for an 84° total field allowing 12 inches of head motion ("pupil" size) around the center of curvature of a 48 inch mirror.

b. A typical focal length of 24 inches would result in an overall thickness under 12 inches.

c. Maximum decollimation would be 9 arc minutes over any head motion and any field angle.

d. No color or distortion over an 84° total field where the only significant aberration is the spherical aberration.

Considering this typical system as a large wide-angle eyepiece, we enjoy the remarkable combination of having an eye relief of <u>160% of the focal length</u>.

In other words the total depth of this new type of infinity display system is scarcely greater than the depth of the sagitta of the spherical mirror employed.

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*Patented - J. LaRussa, 3,443, 858 RE 27,356

This is evident in Figure 1 where the PANCAKE WINDOW[TM] is shown as both pupil-forming and a non-pupil-forming infinity display system. It should be noted from the geometry that the input image source, whether of the screen type or the aerial image type, is substantially smaller in diameter than the PANCAKE WINDOW[TM] as well as being located behind the window and in-line with the observer. These characteristics of minimal depth, in-line input behind the window and input size smaller than the window itself make the PANCAKE WINDOW[TM] ideally suited for mimicking the displays in wide field-of-view systems such as the all-around visual system illustrated in Figure 2.

Referring to the illustration (Figure 3) we see the elements of a PANCAKE WINDOW[TM] in an exploded view while in the lower left hand corner the elements are pictured as they are combined in an assembled window.

In the exploded view there is shown a source of unpolarized light which is usually an extended source.

A first polarizer imposes linear polarization on the light from the source which passes through it. The direction of polarization is identified by the vertical arrow although, of course, any arbitrary direction may be employed. The resultant polarization of the light passing through an element is indicated by the vertical arrow on the flow line. From the polarizer a fraction of the linear polarized light passes through a partially transparent spherical mirror convex toward the source. Beyond the mirror, i.e., to the right in the figure, the linearly polarized light which passes through that mirror encounters a quarter wavelength plate. The plate has its mutually perpendicular fast and slow axes, F and S, oriented at 45° to the plane of polarization shown on the flow line. The linearly polarized light originating at the polarizer which emerges from the quarter wavelength plate is circularly polarized, either right or left according as the angle between the plane of polarization and the fast axis F is 45° or -45°. Let it be assumed that the light emerging from the quarter wavelength plate is right circularly polarized, as indicated by the helical line. This right circularly polarized light next encounters a plane partially transmitting and partially reflecting mirror. The fraction of the right circularly polarized light which passes through the mirror encounters a second quarter wavelength plate whose fast and slow axes, F' and S', are parallel respectively, to the corresponding axes of the prior quarter wavelength plate. Consequently, the light emerging from the second quarter wavelength plate along the direction of propagation has been reduced to linearly polarized light with a plane of polarization at 90° to that of the first polarizer. This is indicated in the illustration by means of the arrow on the flow line. This horizontally polarized light is blocked at a second plane polarizer whose plane of polarization is parallel to that of the first polarizer.

The fraction of the circularly polarized light from the first quarter wavelength plate which is reflected at the plane beamsplitting mirror is converted upon such reflection into circularly polarized light of the opposite rotation, i.e., into left hand circularly polarized light in the case assumed. This is indicated by means of the left hand helix. In its passage backward parallel to the direction of propagation but toward the source, this left circularly olarized light encounters again the first quarter wavelength plate from which it emerges as linearly polarized light with a plane of polarization at 90° to that of the light first polarized. This is indicated by means of the horizontal arrow on the flow line. This horizontally linearly polarized light is in part reflected at the concave beamsplitting mirror without change in the orientation of its plane of polarization. The light so reflected becomes left circularly polarized on passage through the quarter wavelength plate, as indicated by the left-hand helix. The fraction of this left circularly polarized light which gets through the plane beamspiitter is converted by the second quarter wavelength plate into linearly polarized light in a vertical plane of polarization, as indicated by the vertical arrow on the flow line. This light accordingly is permitted to pass through the second plane polarizer and constitutes the only fraction of the unpolarized light from the source which is visible to an observer located at the right of the elements shown in the structure.

This illumination is now collimated. Of course, it goes without saying that if the fast and slow axes of the two quarter wavelength plates are aligned perpendicular to each other, then the first and second polaroids must be aligned perpendicular to one another in order to achieve the same effect. Performance characteristics of the classical glass PANCAKE WINDOW[TM] are listed in Table 1.

3. HOLOGRAPHIC PANCAKE WINDOW[TM] (HPW)

It soon became apparent that with the present state of holographic technology it might be possible to reduce the longitudinal thickness of the standard PANCAKE WINDOW[TM] by incorporating a holographic analog of the spherical beamsplitter mirror, thereby reducing size and weight and also the cost. This holographic spherical mirror analog is produced holographically (photographically) in a very thin and flat gelatin film. Unfortunately however, we soon reasoned that reflection type holograms, typically produced with monochromatic light, exhibit serious dispersion with broadband illumination when viewed in the transmission mode. This property of reflection-type holograms would apparently negate their usefulness in image-forming appartus of the present type which are invariably used with broadband illumination since the light rays to be collimated by the holographic analog must first pass through the analog and be dispersed thereby. After having passed through the holographic analog this dispersed illumination is reflected by a plane beamsplitter back toward the collimating holographic mirror analog, and it was originally assumed that all dispersed light rays reflected from the mirror analog would be collimated for viewing by the observer. This dispersion would completely destroy the usefulness of a system of this type.

However, in the course of experimenting with a holographic mirror analog in an in-line infinity display system we discovered unexpectedly that the dispersed illumination, after being reflected from the plane beamsplitter back to the analog, was effectively filtered by the holographic analog. The analog only reflected and collimated the narrow limited dispersion-free version of the primary image, see Figure 4. The holographic mirror acted as a reflection filter, selecting and collimating a narrow band of illumination from the broadband illumination source.

The holographic analog of the spherical beamsplitter mirror used in this program is a recording of the intensity and phase characteristics of two wavefronts of radiation. These are recorded as intensity variations of the pattern produced by the interference of the wavefronts at the recording plane. After being processed, if properly illuminated, the hologram will reproduce the original wavefronts by a process of diffraction.

The holographic recording material can be modulated only at the surface (plane holograms), or throughout its volume (volume holograms), and can be phase modulated or absorption modulated.

The holograms used in the holographic spherical beamsplitter mirrors (HSBS) are of the volume-phase type. The material to record these holograms is gelatin film photosensitized with ammonium dichromate.

The process is as follows: a gelatin film is hardened to the point in which it just becomes insoluble in water at normal room temperature. The film is photosensitized with ammonium dichromate and upon exposure to light becomes slightly harder in areas where the absorption of the light was greater. After the photosensitized dye is washed out and the film swelled with water, it is rapidly dehydrated. The dehydration and drying create strain areas and material modifications in the volume of the film with local changes in its index of refraction. This index of refraction modulation produces a three-dimensional diffraction grating which is the hologram.

To produce holographically a conical mirror, the film in which the hologram is recorded should be illuminated by two wavefronts, each originating in point sources coincident with its focus. Since a sphere has the two foci coincident in its center of curvature, two wavefronts are used, one emanating and the other converging at the same point which will become the center of curvature of the HSBS (Figure 5).

When the holographic mirror is illuminated, it will diffract light. The diffracted wavefront will have similar characteristics to those of a reflected wavefront from a classical mirror. If the hologram diffracts all of the incident light, it will be equivalent to a total reflecting mirror. If only part of the light is diffracted by the holographic mirror, it will be equivalent to a partially reflecting mirror or beamsplitter mirror.

As a result of Farrand's successful attempt of making a small holographic PANCAKE WINDOW[TM]* the Air Force Human Resources Laboratory (AFHRL) at Wright-Patterson Air Force Base awarded Farrand a contract to develop a 17" holographic PANCAKE WINDOW[TM] which was delivered and accepted. The window is only 5/8 inch thick. Farrand has also made three 21 X 24 inch holographic monochromatic PANCAKE WINDOWS[TM] which are butted together for achieving a multiple input wide field-of-view. These windows are only 3/4 inch thick.

4. TRICHROMATIC HOLOGRAPHIC PANCAKE WINDOW[TM] (THPW)

In 1978, AFHRL recognizing the potential of the holographic PANCAKE WINDOW[TM], and again striving to advance the state-of-the-art in display technology awarded the Farrand Optical Co., Inc., a contract to develop a 21 X 24 inch full color trichromatic holographic PANCAKE WINDOW[TM] (THPW). Farrand completed this window in 1979.

This development has proved to be successful in demonstrating the feasibility of producing a holographic compound beamsplitter spherical mirror with full color response. The production of a red hologram utilized most of the program's efforts and became critical in proving the feasibility of the project. In the context of design goals, all of the basic problems have been resolved with the exception of the resolution of the red hologram which, especially off-axis, needs further development. Poor performance with respect to some specification goals is due to poor manufacturing calibration and short manufacturing time and not to basic or inherent problems.

Continued research and development will be required to produce a tricolor Holographic PANCAKE WINDOW[TM] with a white light transmission close to 1%. The resolution of the red hologram needs to be improved and it is still not conclusive whether or not the construction wavelength is related to the resolution problem. The wavelength shift required using an Argon laser is much larger than using a Krypton laser, but the holographic process is further developed for the green wavelength of the Argon laser than for the red wavelength of the Krypton laser.

The THPW was selected as the optics for AFHRL Project 2363, Advanced Tactical Air Combat Simulation (ATACS). The ATACS is a 3 channel demonstration visual display system incorporating the latest technologies in computer generated imagery, light-valve projectors and holographic pancake windows. A small scale version of the ATACS window was assembled in 1979. Development of a full scale THPW requires an upgrade of the holographic facility to handle holograms larger than 21 X 24 inches. A 48" diameter THPW is required for Project 2363. The small-scale window is actually 70% scale and is full scale, angularly, in that it covers a 90° field-of-view and full scale, resolution-wise. It is 70% scale linear-wise in that aberrations, decollimations and mapping, for example, are 70% scale. This scale window is a marked improvement over the original 21 X 24 inch THPW.

*Patented - J. LaRussa 3,940,203

Mapping, collimation and resolution measurements with both monochromatic light (including laser light) and white light have been taken. It was found that resolution was better for this THPW than the first THPW over all of the window, including the extreme angles, using the white light source. The resolution of this white light source (a flourescent light illuminating a resolution chart) was superior to that of a 10nm wide monochromatic source. It was realized that the fluorescent light has a green narrow spike corresponding to a mercury line (wavelength) superimposed over the continuous spectrum of the flourescent phosphor.

This discovery encourages the investigation of a new approach in illuminating the THPW. This approach consists of illuminating the green hologram with a narrow spike and the other two holograms with a continous spectrum.

The projected and actual performance characteristics of the THPW as compared to the classical glass window are listed in Table 1.

The PANCAKE WINDOWS[TM] as described so far, both classical and holographic, suffer imperfections such as ghosts and bleedthrough. These imperfections are not visible under projected daylight and dusk conditions; they are observable however, under nightime projection conditions when a dark background with bright point light sources for part of the scene.

The ability to see the input in _ directly by looking through the PANCAKE WINDOW[TM] is called bleedthrough and is described in terms of the ratio of the unwanted image to the collimated or wanted image (see Figure 6). Current manufacturing techniques and materials result in a bleedthrough ratio of 1/75 for the classical window. Ghost images are formed by multiple reflections off of the plane and spherical beamsplitter mirrors as shown in Figure 6. Additional reflections forming ghost images beyond the R3 ghost are too weak to be of any concern (0.03% of source in classical glass PANCAKE WINDOW[TM]). In fact, unless the observer is located at the proper distance as shown, the ghost images are invisible and manifest themselves only as very dim background noise.

A recent improvement in PANCAKE WINDOW[TM] design has succeeded in eliminating both bleedthrough and ghost images from the viewing volume. By tilting the birefringent package with respect to the viewing axis as shown in Figure 7, the multiple reflections off of the plane beamsplitter mirror in the birefringent package are directed away from the viewing volume. Since the screen must also be tilted at the same angle, the bleedthrough is also directed away from the viewing volume. The Shuttle Mission Simulator at NASA/Houston is using this display. By tilting the window, ghost images of the stars projected through the optics are virtually eliminated. It is expected that the Tilted Birefringent

TABLE 1

Comparison of Glass and Trichromatic Holographic Pancake Windows

	Full Scale Classical Glass	Full Scale THPW[a]	Best THPW to date[b]
Size (inches)	59, diam	59, diam	21 X 24
Weight (lbs)	600	150	46
Thickness (inches)	12	0.875	0.875
Field of View (degrees)	90	90	90
On-Axis Transmission Efficiency (% of source reaching observer)	1.0-1.5[c]	1.0-1.5[c]	1.3[c],0.3[d]
On-Axis Ghost Transmission Efficiency (% of source reaching observer as unwanted image)	0.03-0.07	0.01-0.02	0.01-0.02
On-Axis Resolution (minutes of arc)	Eye Limited	Eye Limited	Eye Limited

[a]Projected data, to date no THPW has been built which is larger than 21" X 24"

[b]70% scale THPW for Project 2363

[c]Monochromatic light source illumination

[d]White light source illumination

PANCAKE WINDOW* principle can be applied to making a holographic plane beamsplitter mirror in tilted form so that a Tilted Birefringent Holographic PANCAKE WINDOW^{TM} can be manufactured. Such a system would preserve the minimal thickness of the Holographic PANCAKE WINDOW^{TM} while eliminating all ghosts and bleedthrough effects.

CONCLUSIONS

The Air Force anticipates reducing both the cost and weight of visual displays for Air Force flight simulators utilizing PANCAKE WINDOWS^{TM}. The PANCAKE WINDOW'S^{TM} development has evolved from a thick, heavy all-glass assembly to a thin, lightweight optical package employing a holographic spherical mirror analog (Fig 8). The all-glass version of the window has met with considerable success on two Air Force flight simulators and is being considered on others. The Air Force Human Resources Laboratory has pioneered research on the improved PANCAKE WINDOW^{TM} and has sponsored efforts with Farrand for the development of the Holographic Pancake Window. Both monochrome and tricolor holographic PANCAKE WINDOWS^{TM} have been developed and demonstrated by Farrand. Results to date have been encouraging, but these windows must be scaled-up in size to meet Air Force requirements.

AFHRL intends to demonstrate a three channel visual display system incorporating THPWs on Air Force Project 2363, Advanced Tactical Air Combat Simulation in late 1984. These optics will be the largest of their kind ever developed (48" diameter). Farrand's facility will have to undergo extensive modifications to scale up the current THPW efforts (21" X 24") to develop optics up to 60" in diameter, which would be required for A-10 simulator visual displays incorporating mosaicked optical packages, for example.

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*Patented - J. LaRussa RE27, 356.

A-PUPIL FORMING PANCAKE WINDOW™ ASSEMBLY

B-NON PUPIL FORMING PANCAKE WINDOW™ ASSEMBLY

Fig 1 Farrand PANCAKE WINDOW™

INFINITY DISPLAY PILOT ENCLOSURE
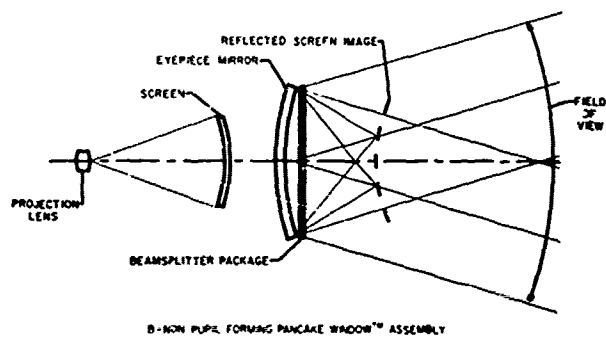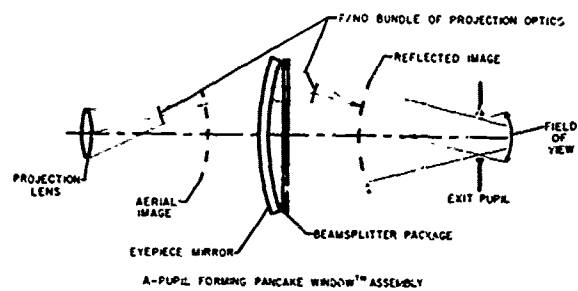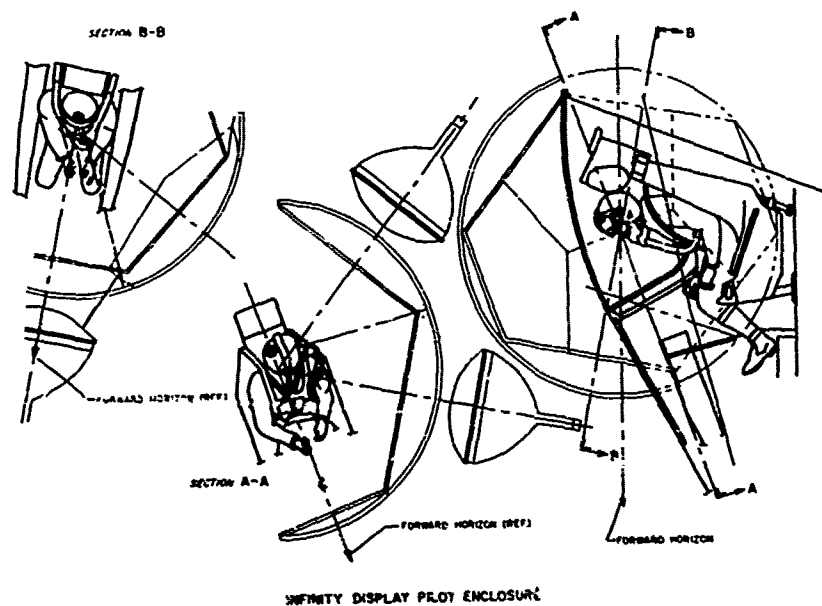
Fig 2 PANCAKE WINDOW™ Sphere of Vision Infinity Display
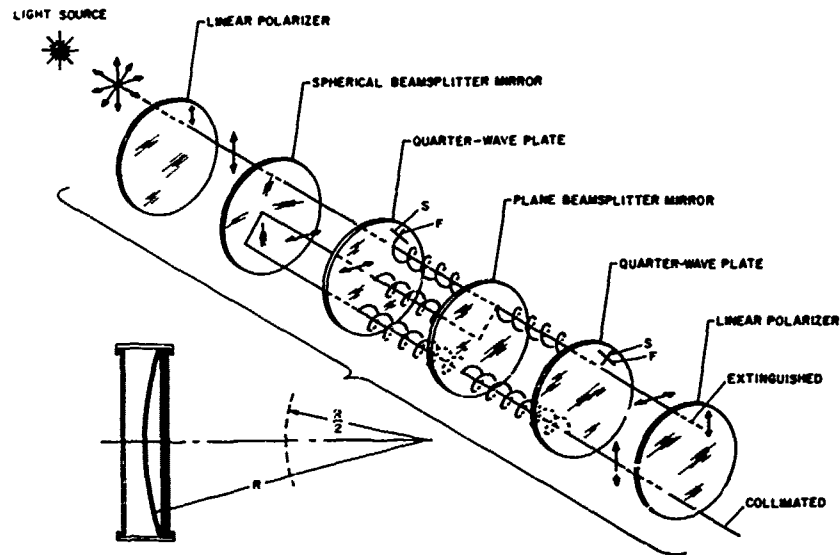
Fig 3 Principle of Operation Of the PANCAKE WINDOW[TM]
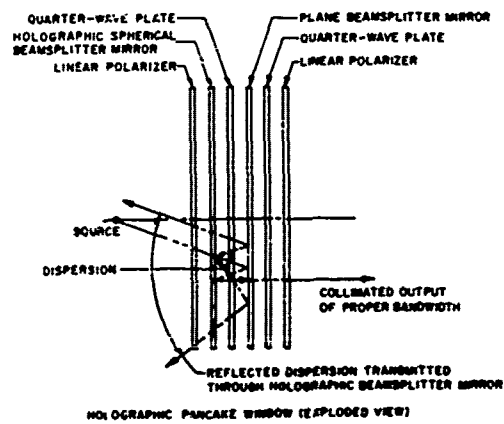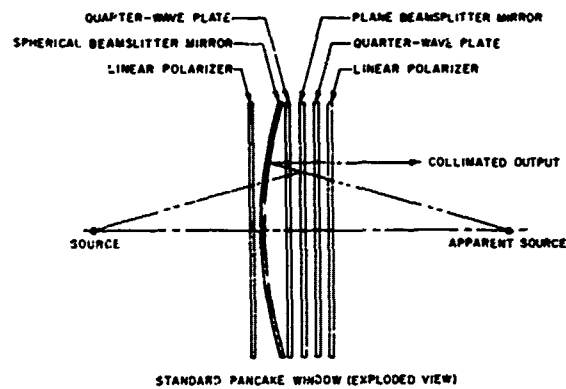
Fig 4 Comparison of Classical Glass and Holographic PANCAKE WINDOWS[TM]

ALUMINIZED MIRROR

HOLOGRAPHIC PLATE

SPATIAL FILTER

LASER BEAM

RADIUS
HOLOGRAPHIC MIRROR

RADIUS GLASS MIRROR
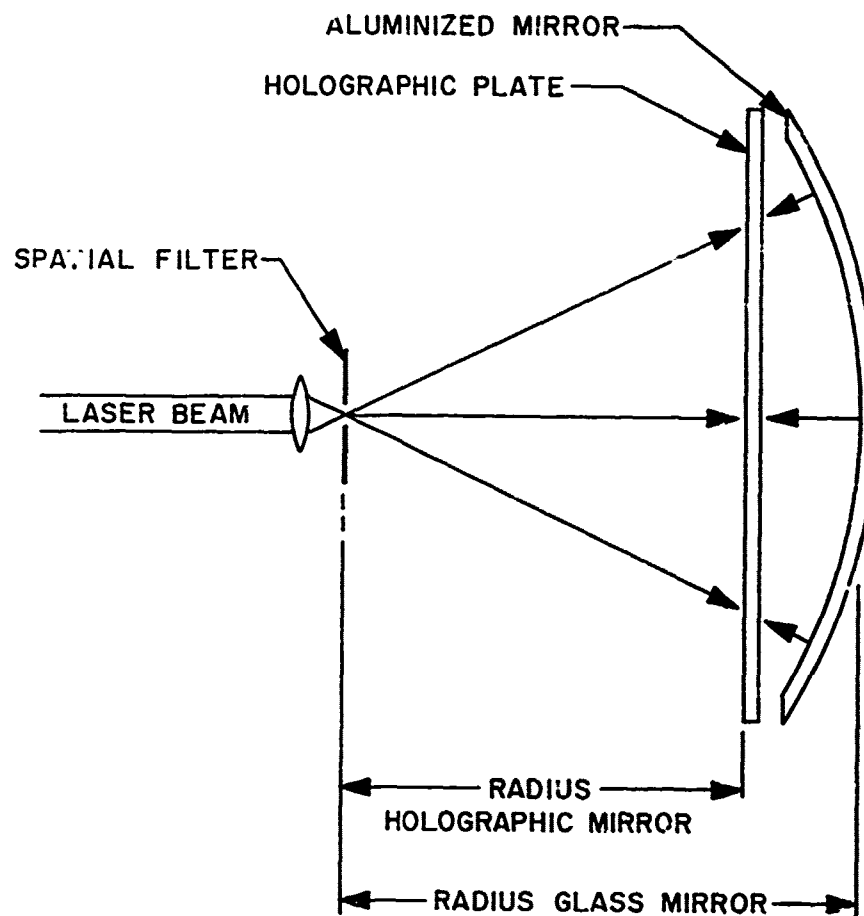
Fig 5 Construction Geometry for a Holographic Spherical Beamsplitter Mirror

1st POLARIZER

SPHERICA. BEAMSPLITTER MIRROR

OBSERVER

A

SCREEN

BIREFRINGENT PACKAGE: QUARTER
WAVE PLATE, PLANE BEAMSPLITTER
MIRROR, QUARTER WAVE PLATE,
2nd POLARIZER

PANCAKE
WINDOW

(A) BLEEDTHROUGH $\frac{1}{75}$ OF WANTED IMAGE

PANCAKE
WINDOW

B

R_2 GHOST   OBSERVER

R_3 GHOST

(B) GHOSTS
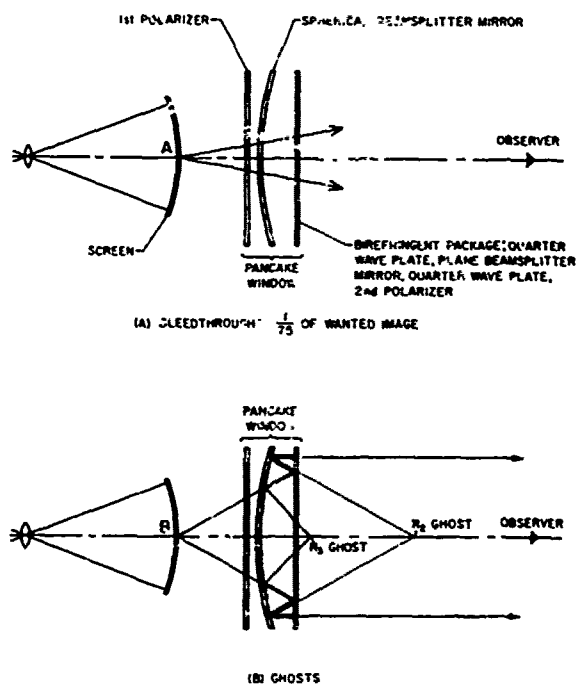
Fig 6 Pancake Window[TM] Imperfections

POLARIZER

SCREEN

BLEED THROUGH

OBSERVER

R_2 GHOST

R_1 GHOST

BIREFRINGENT PACKAGE

SPHERICAL BEAMSPLITTER MIRROR
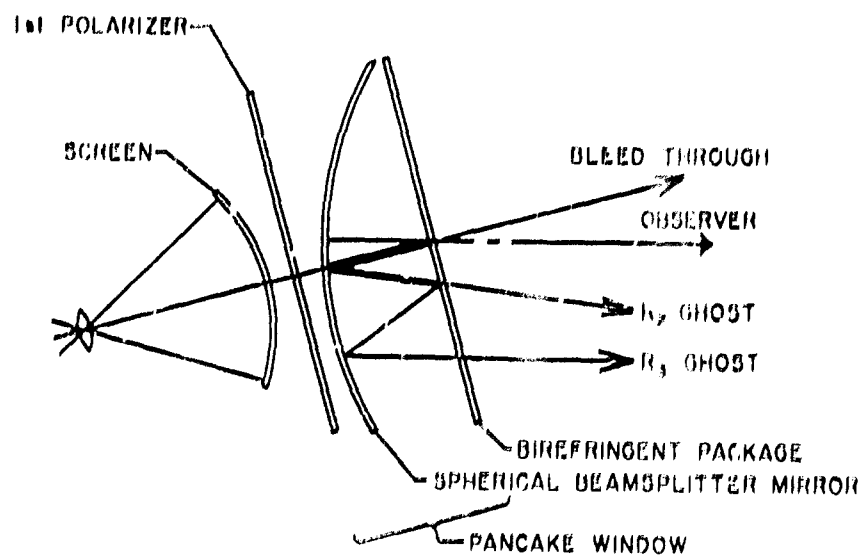
PANCAKE WINDOW

Fig 7 Farrand PANCAKE WINDOW[TM] with Tilted Birefringent
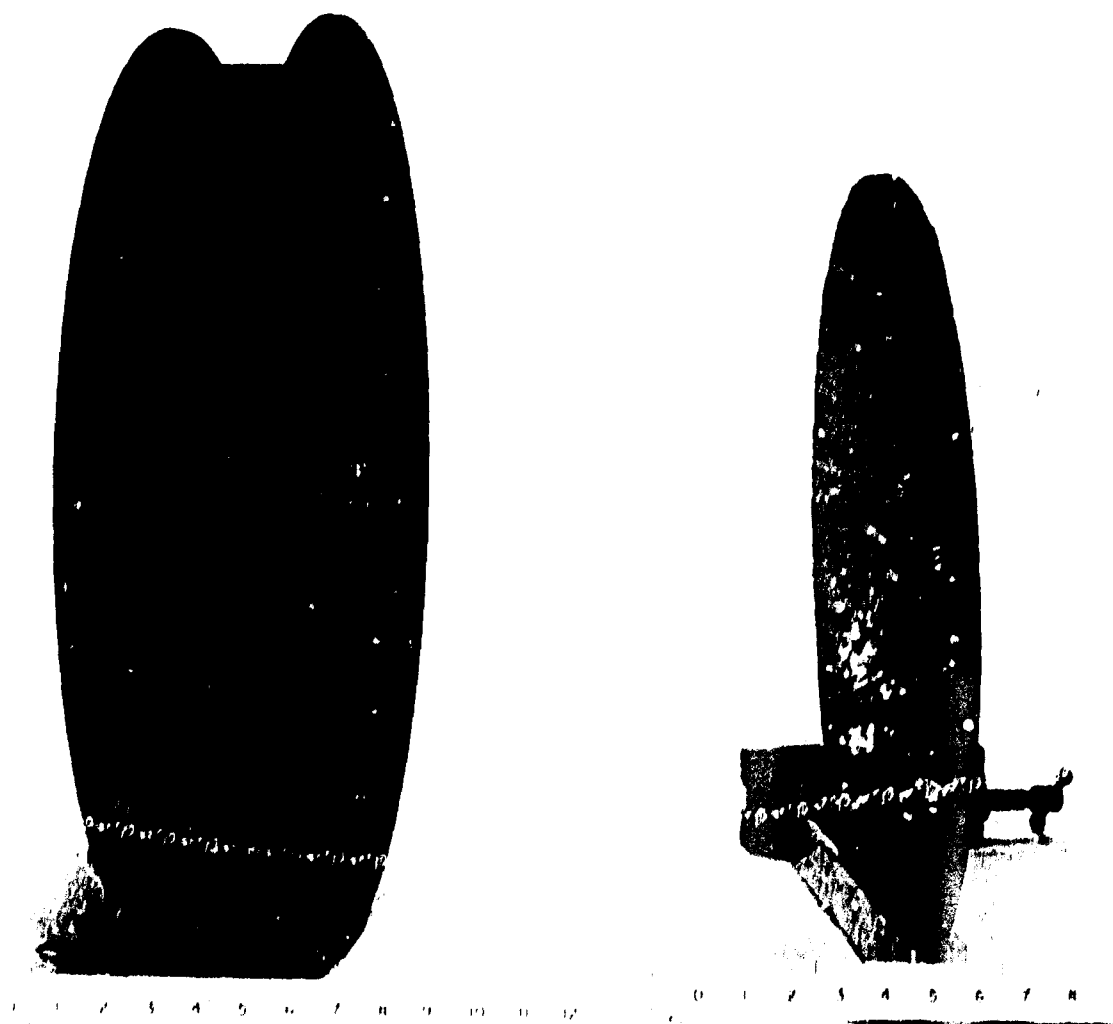
Fig 8 Classical Glass PANCAKE WINDOW[TM] and Holographic PANCAKE WINDOW[TM] Equivalent

EVOLUTION OF TACTICAL AND MAP DISPLAYS FOR HIGH PERFORMANCE AIRCRAFT

by

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SUMMARY

The operational problems which determine the display characteristics of high perfor-
mance military aircraft are particularly exacting in tactical operations flown at low
altitudes over land. Because these operations are related to the terrain, situation
displays having map-like characteristics have become important and are now being embodied
in full electronic display systems for new aircraft. In such aircraft, the need to
conserve display area and handle sensor data in the context of the terrain has led to
combined display techniques. The paper considers the display requirements and the avail-
able technologies. It suggests that the optically combined display based on film storage
is the most notable solution available today although several different electronic
solutions are being or could be developed. Some conclusions as to the relative signifi-
cance of the different alternative solutions are given.

1. INTRODUCTION

The application of advanced technologies to the presentation of information has been
particularly pronounced in the case of high performance military aircraft. These
developments have been forced by a number of factors. The complexity of the avionic and
weapon systems carried has increased, and so the role of the crew as system managers has
become more demanding. High speed operations at night or in low visibility are only
possible with the aid of sophisticated radar or electro-optical sensors which require
advanced displays to realise their full potential. The considerable scope which exists
for new developments in this area is covered in the contribution by Wesley and Blackie (1).

The large amount of data involved in such operations and the automatic functions which
have to be introduced to reduce crew work-load can only be handled by the use of airborne
computers. The resulting system combines human and automatic functions in a complex
manner which places further demands on the designer of controls and displays.

When high performance aircraft are used in a tactical role over land their operations
become closely related to the terrain and to the ground forces occupying it. Flying at
very low altitudes this relationship becomes three dimensional and the aircraft must use
the terrain for defensive purposes as well as following a safe flight path which demands
safe navigation in three dimensions.

All flight display systems involve at least three elements of information. The first
is concerned with the interface between the crew and the various systems and sensors
which together secure the operation of the vehicle and its weapon system. The second
contains the information required by a pilot to fly the aircraft along its planned flight
profile. Because visual clues must also be used for this task such information is
usually displayed head-up. In some cases the inner control loop may be partially or
totally closed automatically, in which case the head-up information assumes more of a
monitoring role. The third significant display area is required to present the pilot
or navigator with a comprehensive picture of the situation against which he can monitor
the progress of the operation and take tactical decisions.

The earliest integrated situation displays were fitted to bomber or transport
aircraft and related heading to displacement from a radio defined track. The relation-
ship to the terrain was established in tactical aircraft through the use of hand held
topographical maps, and the map itself was the most important method of position finding.
It was only possible to contemplate a practical tactical situation display given a means
of determining position continuously and automatically on an area basis, as opposed to
the restricted coverage of radio aids. In fact high speed low altitude flight in jet
aircraft, more complex avionics and inertial navigation have developed together and the
natural trend in display technology has been towards the moving map, driven by the
inertial navigator as a situation display.

The aim of this contribution is to examine those facets of low level operations which impact the situation display requirements, together with the related features of present and future avionic systems. These can be related to the display technologies which are or might be available. It is important to note that in common with other areas of avionics there has been a shift in the balance between operational problems and available technical solutions. The earliest displays were a partial solution to pressing operational problems but the situation is becoming less limited by technology with time. Therefore future choices will be more concerned with optimum solutions which can be implemented in practice and the existence of new technologies will not necessarily be a sufficient reason for their employment.

2. TACTICAL OPERATIONAL REQUIREMENTS

It is important to consider any display in the full context of the operation, as part of a complete suite of displays, and in relation to all the systems which must be operated by the crew.

Tactical operations include close support of ground forces involving relatively short penetration distances and targets which are not precisely located, perhaps because they are on the move. At the other end of the spectrum they may include deeper penetrations to precisely located targets.

The aircraft involved may be single seat or two crew, and this particular choice has considerable effects on the use made of displays. The pilot of a single seat aircraft has to fly, navigate, and operate a wide range of electronic systems concerned with both attack and defence. The pressures are such that he will inevitably wish to fly with his head out of the cockpit as much as possible. Consequently reference to a situation display is made as a brief transition from head out flight and the information content must be chosen to be self-evident, commanding and capable of rapid assimilation. The display functions must be fully integrated with the avionic system controls so that switching operations are minimised.

In a two seat configuration the above considerations apply to the pilot in command but he is backed up by a second crew member who can operate more head down, in which case the display can become a man-machine interface enabling modes of operation in which operator, sensors and computers act together to extract maximum performance from the avionics.

At low altitudes both pilot and system operator are concerned with the terrain :

As a source of features which can be acquired visually or through sensors to monitor navigation accuracy.

As a possible hazard, particularly in low visibility. The only complete protection against striking the ground which does not depend on interpretation of the terrain is that provided by a sensor such as terrain following radar.

As a possible source of protection against hostile fire.

As the contextual background against which possible targets detected by sensors are seen, and as the ground frame within which intelligence data about own or enemy forces can be interpreted.

The above indicate that the requirement is for a display which can combine present position and a projected flight vector against a map-like representation of the terrain. This representation must convey a picture of the external environment in terms which make sense to a skilled pilot flying at low level while in visual contact. It must also form an appropriate context against which to assess information gathered through whatever radar or electro-optical sensors are carried. Finally the fixed information on the terrain must be reinforced by ephemeral information peculiar to a mission, including the programmed flight profile and intelligence data.

The display must take its place in the total cockpit design and provide for all phases of flight, particularly if the available cockpit real estate does not permit a dedicated navigation display and drives the design towards multi-function, multi-mode displays.

To have growth potential any situation display used in a tactical environment must take account of the command and control structure. At present most missions are briefed or even pre-planned, and in flight changes are determined by the crew against a background of relatively poor communications which do not permit closed loop control from the ground. But future developments in communications could introduce some scope for real time control of operations such as exists in the civil ATC system. Such real time instructions would have to be translated into pictorial terms, in the context of all the other information referred to above.

3. THE USE OF MAPS

The human factors considerations in the use of any sort of map are complex and the design processes behind map making are elaborate and expensive. Maps form a deeply rooted part of the professional background of aircrew, who develop skills in their use and interpretation which are hard to define. Any intent to provide a display with map-like features must start from this basis. Hopkin and Taylor (2) have described the human factors involved in map design in considerable detail as well as surveying the related fields of technology upon which the collection, collation and presentation of information on terrain depends.

A simple comparison between a section of a typical topographical map (Fig. 1) and a combination of symbolic and numerical data describing a navigation situation shows the difference in the amount of data conveyed in the two cases. The ability of a skilled pilot to gather an immediate impression of terrain from a map and relate it to what is seen from the cockpit is clearly a complex faculty which must be recognised and accepted even if it is more difficult to explain than most other aspects of display practice.

Hopkin and Taylor (3) confirm that maps do not fit any simple classification of information displays and go on to summarise what is known about human capabilities as constraints on map effectiveness. They distinguish between the sensory and cognitive processes. The sensory limitations are concerned with the eyes response to light intensity (brightness), colour perception and visual acuity which determines the ability to see detail. They can be related to the desirable characteristics of conventional hand-held maps, which have evolved to secure a match between the capability of the average pilot and the reproduction techniques of the cartographer.

The cognitive processes involved in the interpretation of maps are complex and include a combination of serial scanning and information processing. Both Short Term and Long Term Memory are used in the interpretation of symbols and there is in fact a partnership between the cartographer and the user, who depends on the former to display information in a structured manner. There is considerable reliance on learning and an experienced user can look at a map and obtain useful information much more easily than an inexperienced observer. It is important for a pilot to maintain geographical orientation in flight and he quite frequently employs a mental map which goes beyond the coverage of any display.

Where navigation depends on map reading geographical disorientation is a feature of incidents in which aircraft become lost, and is insidious in that it can lead to distrust of instruments and systems.

Within the context of this note we are dealing with aircraft which are basically navigated by autonomous systems such as IN, a map-like display being based on computed position. It is clearly important to display topographical information in such a way that confidence in the system is preserved when it is functioning correctly. Any malfunction should be detected as rapidly as possible, automatically if it is of a catastrophic nature and progressively if it amounts to a system error, in which case the state of geographic disorientation should never be reached. A certain amount of disorientation in terms of the mental map may arise, for example after combat when the aircraft has manoeuvred extensively with the pilot flying head out. It should be the function of the display to rectify such a temporary situation should it occur.

Because existing maps have developed through a long term partnership between cartographer and user they form the basis of common experience and have tended to set the criteria for what is 'best' in any map-like display. It has been pointed out that they are not ideal in content, for example when used in displays or in conjunction with ground mapping radar.

Carel et al (4) have concluded that standard mapping will continue to be used in the future and maintain that future displays should aim to make it more legible by improved resolution, better optics and high image contrast. This reflects a view that economic and production factors will dominate the material available for display purposes, as has been the case so far for most applications of the projected map display. But Hopkin and Taylor (5) point out that UK research has shown that available material can be modified to make it more suitable for display purposes with less cartographic effort than might have been supposed to be necessary.

A major disadvantage in the use of conventional hand-held maps in a modern cockpit is that they are inconvenient to store and retrieve, whatever methods of folding, cutting etc. are employed. The attraction of an automatic display using a condensed data base is that the operational coverage for a theatre can be housed within the system, permitting the use of more than one scale, with the variations in content thus made possible. Future options are largely concerned with the storage and retrieval techniques to be used and with the display technology itself, which should be able to match the facilities produced by the cartographer, including the full range of coded symbols and the use of colour, all reflecting the operational experience incorporated in present maps or variations of them.

The alternative to the use of something very much like the present map is the symbolic chart, conveying much less information and thus much easier to store, retrieve and present. This solution has been used with success in civil aviation where operations are referenced to an Air Traffic Control structure of airways, control boundaries, radio facilities and standard arrival or departure procedures. The significant difference between the civil

requirements and those considered here is that commercial aircraft do not operate by
refe nce to the actual terrain. Civil pilots operate procedurally and 'head in'. The
most obvious tactical equivalent occurs over the sea where maritime aircraft operations
can be handled quite easily using symbolic displays.

The best assumption which can be made about tactical aircraft operating low level is
that the mapping material used in displays will continue to resemble that used now with
the possibility of variations achieved as the result of experience, particularly as the
requirements of radar map matching are given more weight.

4. FUTURE DEVELOPMENTS IN CARTOGRAPHY

It is desirable that longer term display developments should have the growth
potential to absorb future developments in the design and production of map material which
will occur under the pressure of new requirements, or new developments in the system field.

There is a trend to develop radars with superior resolution, as pointed out by Wesley
and Blackie (6). It is probable that radar predictions will be required to use this
potential fully. It is possible to derive such predictions from a digital cartographic
base, although it is thus implied that each mission must have a prediction for the route
envisaged. This concept is being realised in the Digital Radar Land Mass (DRLMS)
programme.

However whether or not the infrastructure involved in data base production will be
required in practice depends on the operational benefits to be gained from the use of
high precision radar for navigation, as opposed to its use for target detection. It
does appear that navigation of enhanced accuracy could result from more than one current
or proposed development programme. Navstar (GPS) is scheduled to be deployed in the
1980s with a projected accuracy of better than 10 m. The combination of precise IN and
GPS, or alternatively updates derived visually or through electro-optical sensors, should
control navigation accuracy to limits which would make sophisticated radar updating an
unnecessary adjunct to navigation.

Navstar could have a major impact on map making for the separate reason that existing
grids may be rendered obsolete, being replaced by some sort of universal GPS grid. But
here again it is true that the detailed cartographic base available now would be
expensive to rework in its entirety and display users, like all navigators, will have to
adapt to the best material available for any given area at any given time. This includes
adapting to the manner in which the data base is accessible. While map material may
reside in digital form at some point in its editing and preparation by the cartographic
agencies it is not easy to predict how or when a user will be able to acquire map material
with an agreed content in digital form for direct on-line use.

In the same way a digital data base giving the distribution of ground contours can be
of immediate value to a user who wishes to navigate using correlation techniques,
provided that his desired operational coverage is available to a resolution compatible
with his accuracy requirements. But to be suitable for display purposes such a data
base would also have to be edited to include the features required in a meaningful
display. Hopkin and Taylor (7) have shown that the present 'acceptable' content of
aeronautical maps is the result of a long standing interplay between cartographer and
user, and that even today's maps, which have been criticised as a display medium,
represent the result of an evolutionary design process which was not easy to achieve, and
could still be improved greatly.

The terrain viewed from a low flying aircraft rolls into view as a perspective
extending to the visible horizon. Prominent features appear with an aspect which
depends on their location relative to the planned track and their altitude relative to
the aircraft. There can be extensive screening in undulating terrain and even over flat
country when roads, railways or canals are blanketed by the lie of the land. Electro-
optical sensors, like the pilot's eye, will see the terrain from this operational aspect.
In contrast, map material is prepared in plan, and requires considerable interpretation
at low altitudes. It is more likely that pilots will acquire particular features as
check points, using their acquired skill to effect a coordinate transformation. It has
been suggested that a digital data base could be manipulated to produce a perspective
situation display which would then correlate more easily with sensor information.

A strategy is required to permit any of these developments in cartography or data
handling to be exploited as and when they become available in a convenient form, which in
turn implies that any modern display should be able to access and generate computer
symbology to a degree of complexity fixed by the display surface limitations.

But the main thrust in the development of situation displays with a significant
topographical content is still likely to be towards the reproduction, with the highest
possible image quality, of coloured material drawn from the main stream of aeronautical
map development. This main stream will be influenced by new navigation requirements and
by its users, but relatively gradually.

9-5

5. FUTURE DISPLAY DEVELOPMENTS

It is now possible to draw together the requirements for a state of the art situation display for a tactical aircraft and to indicate where or how new technologies may be profitably introduced.

The display should be capable of being integrated into a typical multi-mode/multi-function display suite. It should have a powerful electronic display element capable of being interfaced with the mission avionics through a data bus, and thus capable of accepting whatever formats are made available in the future. Their availability will expand as digital data bases of fixed or ephemeral tactical information become available, including real time command data. The information displayed in different phases of flight will be determined as part of the overall system design.

The electronic display should be readable through the full range of ambient light conditions from night to bright sunlight. It should be able to handle coloured symbology as an option. It should be designed to be positioned high in a single seat cockpit, contiguous with the Head Up Display, thus also meeting two seat requirements.

For tactical operations over land a map-like presentation is highly desirable for reasons given earlier. The operational and human factors arguments stated earlier reflect the present state of knowledge and research and point towards a requirement for a high resolution full colour map display associated with the versatile electronic component. The evolution of map material appears to be such that the display should be able to exploit the main stream of such material, however it is produced at present or may be adapted in future as a result of the interplay between cartographers and users.

The technologies used will depend largely on the baseline already in existence. The COMED display described by Aspin et al (8) has achieved a high quality by the evolutionary development of the details of optical combining. It is supported by a comprehensive infrastructure for the preparation of data using a most convenient high resolution medium: 35mm film. The data is degraded as little as possible by the configuration in which the film is directly viewed within the display head. This is also probably the most economic configuration in terms of total installation volume.

It is clearly possible to exploit the same data base (film) within a separate LRU housing a film transport, remotely scanned to produce a full colour TV output in composite video or similar form. At present means exist to combine raster symbology with the above by mixing, or to generate symbology by stroke writing in the fly-back period. Such a map generator would be immediately compatible with an all-electronic display suite but the full potential of the data base would only be realised in conjunction with a full colour display head. Based on present experience this should be capable of resolving three line pairs per mm and of adequate contrast to be viewable under all conditions or ambient light in a military cockpit. In the present state of technology, this would have to be based on a ruggedised shadow mask or similar CRT.

The two closely allied solutions, the combined display and the pure electronic display can be contrasted as follows. The viewability of a pure, full colour electronic display in sunlight will depend on:

(a)   The development of a tube of adequate brightness in all three primary hues.

(b)   The development of a polychromatic filter capable of maintaining contrast without significantly degrading resolution.

In contrast, Aspin (8) has pointed out that COMED produces an image which is viewed through a field lens system which excludes ambient light by generating an exit pupil centred on the pilot's head. He has also described other advantages which lead to a bright image using a CRT with reduced dissipation.

There is clearly a reliability penalty associated with the pure electronic display solution in that additional electronics to scan the film transport are required. In addition, the relatively large colour CRT may well have failure modes not applicable to the small monochrome CRT used in COMED to superimpose symbology or other raster information.

The single COMED Unit interfaces with the avionics through a single digital interface for control purposes and a conventional display head interface. It is therefore an easily tested sub-system contained within a single LRU. In contrast a map generator solution leads to an additional LRU for which space in an equipment bay must be found.

The single unit COMED solution has a further advantage, particularly in a single seat cockpit in which space is limited, so that the total number of display surfaces must be minimised. Because the film can be viewed directly the display will survive a failure of the electronic element and still provide a navigation situation display. Essentially, there is dissimilar redundancy and considerable elegance in the fact that the pilot can view the data store as directly as possible.

Clearly, both of the above solutions are compatible with the main stream of pictorial map material, however produced.

Longer term developments beyond the above are possible as a result of the emergence of new technologies. The successful production of an alternative to the CRT as a colour display surface would have a considerable impact on displays of all kinds. New monochrome or two colour solutions might be acceptable for many display requirements, particularly if the new devices had other major advantages for use in avionics. But it is not established that solutions other than full colour can present a totally meaningful display of terrain features except by resort to unconventional mapping materials.

It has also been suggested that with continued advances in digital technology it should be possible to develop, store, retrieve and display mapping material by an entirely digital chain of processes. For these developments to establish themselves in operational use it is necessary to assume the existence of:

An acceptable map-like data base with content proven to be acceptable to pilots, which implies much development of cartographical software and editing facilities.

Comprehensive ground computer facilities to permit a mission data base to be formed within the limitations of available airborne computer storage. The technology for the latter must be assumed to exist as bubble memories etc.

Powerful proven airborne software to retrieve and manipulate the data for use within an equally powerful high resolution graphics generator. These appear to fall naturally within the technologies already under development.

The crucial user problem seems to be the emergence of a data base to compete with the film data base already in use. It will also be very difficult to compete with film in terms of information density and resolution. Even with the introduction of one megabit bubble memories the sheer volume of the digital store capable of covering an adequate area of terrain, in colour and with adequate detail, is still a major potential source of system complexity.

The video tape is an alternative medium which has not so far been mentioned. Although it is an established technology it represents an alternative set of editorial and logistic problems which it is possible to escape. As with the use of film, a complex mechanism is required to drive the tape but, unlike film there is no compensating advantage of direct viewing and subsequently high resolution. The high speeds at which the tape must be scanned to produce an image of acceptable resolution pose an additional reliability penalty. The ephemeral nature of video tape is probably more of an advantage in other fast-moving applications such as those in which it is already widely used.

6. CONCLUSIONS

It has been shown that tactical aircraft operate in close proximity to the terrain and that the most natural situation display therefore has map-like characteristics.

Present maps have resulted from a long interplay between cartographers and users. Although they are not always ideal for display purposes maps from this main stream of development are likely to form the basis of future displays. Their optimum display demands high resolution colour.

There is a high element of skill in a pilot's interpretation of the terrain as seen visually or through sensors against a map in plan form. Unconventional projections secured by software are possible but the element of skill will probably predominate. Sepcial maps for radar matching are possible but may be less necessary for navigation with the advent of precise IN or Navstar.

The optically combined display already provides high resolution colour as well as being compatible with a full electronic display suite. It provides a form of dual redundancy and instals in a single LRU. An alternative using the same data base is the remotely scanned map, which depends on the availability of a full colour high resolution CRT embodying a proper solution to the problems of high ambient light. The direct view of the store in the combined display is elegant, and assures optimum optical quality.

The all-digital solution is a possibility which awaits a viable solution of the editorial and logistic problems of a digital data base together with a proper full colour display head. There are considerable digital hardware and software problems and the storage required could be massive, even in terms of devices such as bubble memories. Bearing in mind the complexity of cartography as an activity and the long history which has led to present mapping material it would be a considerable task to demonstrate that such a system is operationally superior to a combined display based on film, or acceptable in human factors terms if it is different.

It does appear that with the combined display and other complementary display and digital techniques we have the building bricks for a range of systems which will evolve in future but be stable in technology, giving considerable scope for the development of new operational and system concepts. There may be a discontinuity in this and other display areas if and when a radically full colour solution using some new display surface is achieved, but this subject is outside the scope of the present contribution.
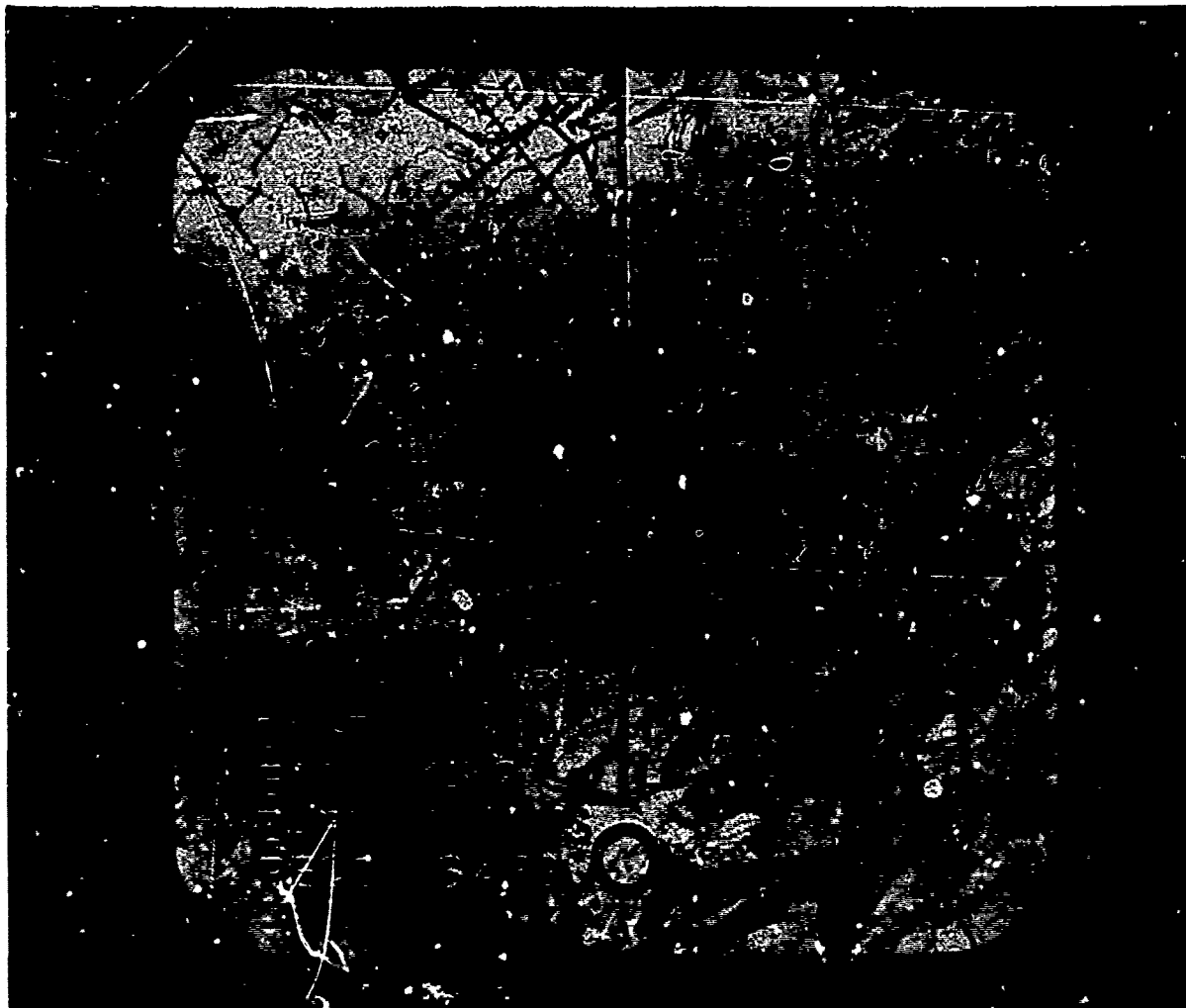
Figure 1

A typical Topographical Display with Symbology
overlaid to describe a simple navigation/tact-
ical situation. Note the vast difference in
information content, even over relatively
featureless terrain. Also the advantage of
symbols placed in context with terrain.

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HELMET MOUNTED DISPLAYS: DESIGN CONSIDERATIONS

by

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SUMMARY

This paper describes several parameters that must be considered in the design of a helmet mounted display (HMD). The parameters discussed include: size, weight, exit pupil, eye relief, field of view, collimation, distortion, image quality, and several others. Detailed discussion and specific related equations are provided for many of these variables. Optical design approaches to HMD's are discussed with reference to specific systems that have been fabricated. A summary table is included that shows the values of many HMD design parameters for six HMD's. HMD image sources, both present and future, are presented. Ample references are provided for those seeking more details concerning HMD's.

INTRODUCTION

A helmet-mounted display (HMD) is a device attached to an individual's helmet that produces a virtual image display visible to the wearer of the helmet. The displayed image may be only a simple reticle or may be complex imagery from an imaging sensor such as a forward-looking infrared sensor. Often the HMD is used in conjunction with a helmet-mounted sight (HMS). The HMS is a device that is capable of determining the helmet line of sight using remote sensing techniques. When used together, the HMD/HMS combination is called a visually-coupled system (VCS). The HMS determines the helmet wearer's line of sight; the signals produced by the HMS drive the sensor used in the system such that it points in the same direction as the helmet. The imagery from the sensor can then be displayed on the HMD. Thus the sensor is coupled to the helmet line of sight by the HMS, and the imagery produced by the sensor is displayed to the observer on the HMD, forming a closed loop system. Figure 1 shows pictorially the HMD concept.

Fig. 1. Helmet-mounted display
(HMD) concept
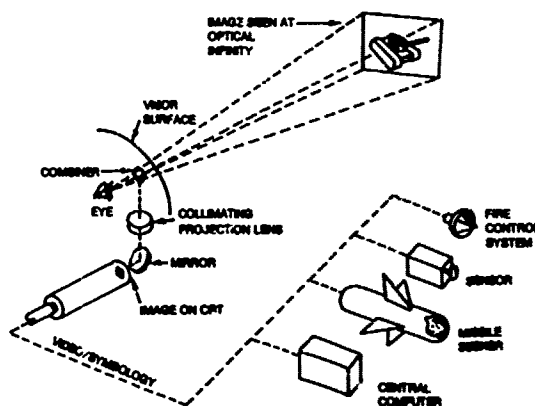
Many techniques have been developed to produce working HMS devices. Since it is not the objective of this paper to provide further information on the HMS, the interested reader is referred to reference [1] wherein several HMS techniques are presented. The purpose of this paper is to acquaint the reader with the HMD. Several HMD's have been constructed using different techniques and image sources for a variety of applications and mission conditions. Design parameters for HMD's are discussed in detail. Selection of appropriate values for many of the HMD design parameters are specific to the particular application and should be selected carefully to insure a useable display. A comparison table of many of these design parameters is provided showing typical values for existing HMD's.

HMD DESIGN PARAMETERS

There are many design parameters associated with HMD's. Careful consideration must be made in specifying these to insure the operational utility of the HMD for the particular

application. Desired values of many of the parameters change depending on the application for which the HMD will be used. Table 1 provides a list of the design parameters discussed in this section.

Table 1   HMD Design Parameters

Size/weight/center of gravity	Image to ghost ratio
Monocular vs. binocular	Color/color contrast
Exit pupil	Modulation transfer function
Eye relief	Image source quality
Apparent field of view	Roll stabilization compatibility
Collimation	Combiner reflectivity/transmissivity
Distortion	System transmission efficiency
	Safety

Size/Weight

Since the HMD is supported by the viewer's head, the weight and size increase caused by the HMD must be minimized. This factor is a direct trade-off with the following four design parameters. A binocular HMD weighs more than a monocular HMD. Increases in exit pupil, eye relief or apparent field of view tend to cause an increase in the optics resulting in increased size and weight. These are discussed in greater detail in [2]. Weight increases can be partially offset by using plastic optical components and housings. However, plastic lenses are easily scratched and should not be used in places where they are exposed.

Monocular vs. Binocular

By far the most common HMD has been monocular. The advantages of a monocular HMD are smaller size, less weight, easier alignment and lower cost. The binocular HMD does, however, provide an image to each eye. This prevents any possibility of binocular rivalry occurring if the two images are identical or are a stereo pair. There has been concern with the potential for binocular rivalry in monocular HMD's for many years. Several studies have investigated the question of binocular rivalry in HMD's [1], [3], [4]. Many parameters (luminance, contrast, etc) have been shown to have an effect on the subjective incidence of binocular rivalry [3]. In general, the more disparate the images to each eye, the greater the possibility for rivalry to be a problem. HMD's that present symbology only (no imagery) at a luminance level compatible with the external scene luminance show little or no potential to induce rivalry. In the application where the HMD displays imagery from a sensor, the potential for rivalry increases. The severity of this effect has not been determined. Individuals involved in HMD activities vary in their opinions from indicating that there is no rivalry problem to insisting that the problem is severe. However, most agree that the susceptibility to binocular rivalry depends heavily on the individual and the specific display conditions.

Exit Pupil

The exit pupil of an optical system is the image of the aperture stop of the system as viewed from the image space of the system [5]. In practical terms for HMD's, the exit pupil determines the extent to which the eye can move laterally with respect to the display (helmet) before the image is no longer visible. For example, if the exit pupil is a circle of diameter D then the eye can move a distance (D-d), where d is the pupil diameter of the eye, to the other side of the exit pupil before vignetting due to the entrance pupil of the eye occurs. This assumes that the exit pupil of the HMD does not suffer from vignetting due to other parts of the HMD optical system. Whenever possible the exit pupil diameter should be specified as not vignetted. (i.e. "exit pupil diameter shall be 15mm with no vignetting.") The reason for a large exit pupil is to prevent loss of the HMD image due to vibration or helmet slippage. Adjustment should be provided so that the exit pupil of the HMD can be centered on each observer's eye. Note that as the eye is directed at different parts of the display it rotates about a point within the eye. This causes the pupil to move laterally with respect to the HMD exit pupil. Sufficient exit pupil must be provided so that the eye does not move out of the exit pupil when scanning a wide apparent field-of-view HMD. This problem is minimal or nonexistent for narrow (5°-15°) field-of-view HMD's.

Eye Relief

The eye relief is the distance from the eye to the final element of the optical relay system. It is desirable for this distance to be relatively large (greater than 15-20mm) to prevent the HMD optics from interfering with the observer's eyelashes and for safety reasons. If the observer is permitted or required to wear eyeglasses, this distance must be increased accordingly. Typically as this distance increases, the center of gravity of the HMD optics is shifted forward and it becomes more difficult to produce a wide apparent field-of-view.

Apparent Field-of-View

The apparent field-of-view (FOV) is the angular subtense of the HMD image as viewed from the observer's eye. Figure 2 shows the relative angular size for several displays viewed from about 48cm in comparison to a 40° FOV HMD. HMD's have been fabricated with fields-of-view ranging from 5° to 40° along the diagonal dimension. An 80° field-of-view HMD has been designed by Farrand Optical Company, Incorporated and is under construction for a ground-based application. The necessary HMD field-of-view depends on the specific application for which the HMD will be used. For symbology-only applications, 5° to 15° is usually adequate. For target acquisition and imagery viewing 20° or more is desirable and in some cases, required. For piloting and checkpoint navigation much larger fields-of-view are desirable (40° or greater). As field-of-view increases, size and weight also

i:..:ease since larger, more complex optical systems are needed. Eye relief and exit pupil diameter may have to be decreased t> accommodate the field-of-view increase.

Fig. 2. Relative angular size of several displays as viewed from 48cm in comparison to a 40° field-of-view HMD

8" PANEL-MOUNTED DISPLAY

40° FOV HMD APPARENT IMAGE SIZE

12" PANEL-MOUNTED DISPLAY

A-7 AND F-4 DISPLAY
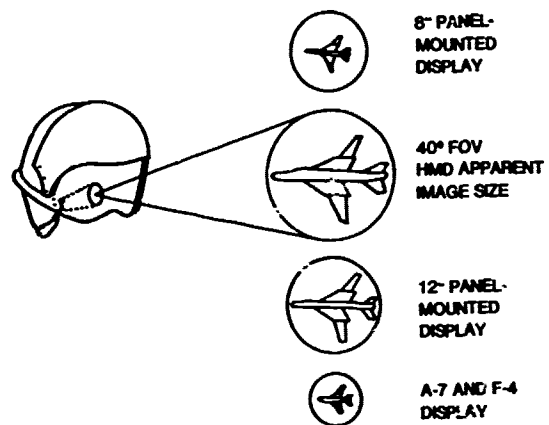
Collimation

Most HMD applications require that the HMD image appear to be at optical infinity (very far away). This is equivalent to stating that the image is collimated. The advantage of collimation is that there is no parallax between the HMD image and distant external scenes upon which the HMD image is overlayed. This is important for target acquisition. If the image is not collimated, then the image (e.g. a sight reticle) would move with respect to the target as the eye shifted laterally in the exit pupil. For other than direct target acquisition applications it may be desirable not to have the image collimated. For example, if the HMD is used for viewing sensor imagery it may be desirable to fix the image location in the same plane as the instrument panel, thus permitting the wearer to switch between the HMD image and the panel instruments without changing his eye accommodation distance. This may also decrease the potential for binocular rivalry for viewing outside the aircraft as the observer would "look through" the HMD scene when observing the exterior scene although some studies have not shown this effect for subjective rivalry assessment.

Distortion/Aberrations

Distortion occurs as a result of nonlinear transformations from the image source through the optical system. Typically, distortion appears as a "barrel" or "pincushion" in rotationally symmetric optical systems as shown in Fig. 3. However, HMD's using a parabolic visor as an optical element in the HMD optical chain suffer from a "parabolic" distortion (see Fig. 4).

A   B
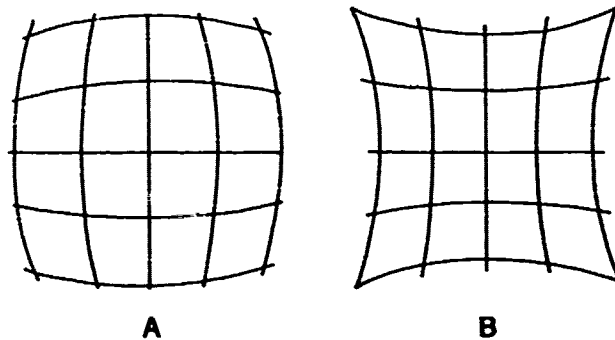
Fig. 3. Typical distortion in rotationally symmetric optical systems A)Barrel distortion, B) Pincushion distortion
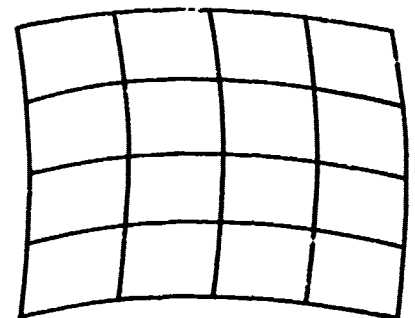
Fig. 4. Parabolic distortion increased by use of the parabolic visor

Barrel and pincushion distortion may or may not be severe enough to require special correction but "parabolic" distortion does. In general the distortion and other aberrations are reduced as the number of optical elements is increased; however, this causes an undersirable increase in weight. A reasonable compromise between number of elements (weight) and optical aberrations must be achieved. Also, depending on the technology used, a particular optical design may employ either "F(θ)" or "Tan(θ) mapping. For F(θ) mapping the image field angle is proportional to the image source chordal height, whereas, in Tan(θ) mapping the tangent of the field angle is proportional to the chordal height of the image source. The characteristics of the image source must be matched to the type of optical mapping. Field curvature and astigmatism may also present problems especially as the field-of-view for a particular design is increased. Field curvature can easily be corrected by attaching an appropriately shaped fiber optic

faceplate to the image source. Distortion and mapping problems can be corrected by the addition of compensation electronics within the CRT deflection amplifier signal path. An often used approach to this problem is to first generate a mathematical representation or least squares fit of the distortion which must be compensated for and then determine the number of significant coefficients for a given percent decrease in distortion at the observer's eye. The selection of these coefficients must also be balanced against what represents a practical requirement for the electronics hardware. Critical for the hardware is the small signal bandwidth requirements that the compensation electronics must meet based upon either the highest line rate at which the system must operate in a raster mode or the step response/settling time characteristics for a caligraphic mode of operation. Due to the methods which most analog circuits use to generate terms with arbitrary exponents, the inclusion of a second order term will approximately double, and the addition of a third order term will nearly triple, the bandwidth requirements for the compensation circuits [6]. Depending upon small signal bandwidth requirements, the inclusion of only a few higher order compensation terms will, with current technology, severely strain state-of-the-art performance for the analog multipliers that are generally used in such applications, as well as the signal-to-noise performance of supporting electronics. The above considerations are an illustration of the necessity for considering all components of the helmet-mounted display system early in the design development process so that appropriate trade-offs can be made.

Image to Ghost Ratio

Most HMD's employ a beamsplitter or combiner that "combines" the HMD image with the external world scene. The combiner is typically coated on one side (closest to observer's eye) to increase the apparent luminance of the HMD image. However, some reflection also occurs at the other surface. If the combiner is flat and the image is collimated then the ghost image forms directly on top of the primary and no problem is encountered. If the image is not collimated or the combiner is not flat (e.g. parabolic or spherical) then the ghost image may appear slightly to one side of the primary. This is particularly noticeable when the HMD is used for night symbology applications. The image to ghost ratio can be calculated using the following equations.

The apparent luminance of the primary image is:
$$L_p = L_I r_c \qquad (1)$$

where:

L_p = luminance of primary image

L_I = luminance of the image prior to combiner

r_c = reflectance coefficient from coated combiner

The apparent luminance of the ghost image is:
$$L_G = L_I t_c^2 (1-a)^2 r_2 \qquad (2)$$

where:

L_G = luminance of the ghost image

L_I = luminance of the image prior to combiner

t_c = transmittance of combiner

a = absorption coefficient

r_2 = reflectance coefficient for outside surface·

Thus the image-to-ghost ratio is:
$$R = \frac{r_c}{t_c^2 (1-a)^2 r_2} \qquad (3)$$

If the visor coatings are wavelength sensitive, then the spectral reflectance, transmittance, and absorption curves must be used with integration over wavelength. Note that for night HMD applications it is desirable to keep the combiner as transparent as possible. As an example, assume that no coating is used and the combiner is made of clear plastic. This would yield the following approximate values:
$$r_c = r_2 = 0.04; \quad t_c = 0.96; \quad a = 0$$

For these values, the image to ghost ratio would be:
$$R = \frac{0.04}{(.96)^2 (1)^2 (0.04)} = 1.085$$

This indicates the ghost image would be almost the same apparent luminance as the primary. For day HMD applications the combiner is usually made of a dark-tinted plastic (a=0.85). With a moderate reflective coating (r=0.30, t_c=0.60) the image to ghost ratio is greatly improved:
$$R = \frac{0.30}{(0.60)^2 (1-0.85)^2 (0.04)} = 926$$

Color/Color Contrast

Most HMD's constructed to date use a monochrome image source such as a miniature cathode ray tube (CRT) or a light emitting diode (LED) array. The CRT's use a green (P-1, P-44, P-43) or red (P-22R) phosphor and the LED's are red (λ = 650nm). The effect of the narrow band color is to make the HMD image more easily visible than would be expected

from the photometric contrast values measured for these devices. This color-contrast effect should be investigated further to improve the visibility of the HMD image.

Modulation Transfer Function

The modulation transfer function (MTF) of an optical system describes the ratio of output contrast to input contrast as a function of spatial frequency for a test pattern that varies sinusoidally in intensity (luminance) along one dimension. The MTF has a value of unity at zero spatial frequency and usually decreases monotonically as frequency increases. The image quality of continuous (not sampled or discrete), linear imaging systems is probably best determined from MTF information. It is particularly well suited for describing the image quality loss (reduction in contrast) due to external scene transmittance through the HMD combiner. Further information of MTF as it applies to CRT displays can be found in references [7], [8], [9].

Image Source Quality

There are several devices that have been used for, or are under development for, imaging sources for HMD's. The simplest of these is a set of five incandescent lamps used to project a reticle and four information/status lights. The most widely used is a miniature (25mm diameter by 125mm long) CRT. Other devices include a light-emitting diode (LED) array, a liquid crystal (LCD) array and an electro-luminescent (EL) panel array. These latter solid state devices are more recent and are presently under development to achieve higher element densities [10] compatible with HMD image source requirements.

There are several parameters associated with image quality of imaging displays[8] It is not the objective of this paper to treat the image quality area in detail. However, the following table lists the parameters that are probably of the most importance to the image quality of CRT and solid state displays. Note that such parameters as limiting resolution, contrast ratio and number of gray shades can be determined from the MTF [7].

Table 2. Image Source Quality Parameters

CRT image quality parameters:	Solid state display image quality parameters:
Modulation transfer function	Total number of picture elements
Peak luminance	Peak luminance (for LCD this includes
Number of active scan lines	illumination)
Scan line spacing/percent line	Adjacent element contrast ratio
pairing	Percent active area

It should also be noted that strictly speaking an MTF does not exist for the solid state displays as they violate the continuity requirement (they consist of discrete elements). Therefore, the best measure of "resolution" for the solid state imaging devices is the total number of picture elements or "pixels". This number will determine if the device is capable of producing imagery or has only sufficient quality to display symbology.

Roll Stabilization Compatibility

When the HMD is to be used in airborne applications or in aircraft simulators for presenting either scene background imagery or graphics, such as a space-stabilized HUD, it is desirable to provide derotation of the display imagery with respect to the horizon and/or aircraft. Thus when the observer rolls his head, the appropriate portions of the HMD imagery roll in the opposite direction to maintain stability with the actual horizon. To accomplish such derotation it is necessary to employ a helmet-mounted sight system which measures not only head azimuth and elevation but roll as well. The sensed head roll about the observer's line-of-sight can then be fed back to the graphics processor and/or to the display electronics so that appropriate signals may be generated in the deflection amplifier circuitry to derotate the imagery on the CRT. There are several areas which must be considered if the derotation is to be effective. First, the image source and relay optics of the HMD must be capable of accommodating this rotation. In particular the image source must be capable of rotating the image and the relay optics must have a large enough clear aperture to allow the rotation. Solid state displays may have greater difficulty in accommodating these requirements than the standard CRT since their pixels are typically fixed in a rectilinear array. For in-raster presentations another problem arises, especially if higher line rates and resolution is required. A consideration of the following example illustrates this problem. Suppose that a 1225 line system capable of 1024 x 1024 active pixel elements requires derotation compensation. If multiplicative errors that will cause display discontinuities are not to be a problem then sufficient resolution must be provided across the image source. A good subjective value is to hold display discontinuities due to derotation to about 12.5% of the line width. This requires 12 bit resolution (0.025%) which is beyond the current capabilities of analog multipliers that might be used in the HMD electronics. This forces one to consider the use of a 12 bit multiplying D/A connector. However, depending upon the bandwidth and signal-to-noise performance required, one may quickly find himself pushing the state-of-the-art for these devices.

Combiner Reflectivity/Transmissivity

The selection of the combiner coating, which determines the combiner reflectance and transmittance coefficient, is probably the most critical HMD characteristic to be specified. This fundamentally determines the ratio in luminance between the HMD image and the external world scene. The maximum modulation contrast of the HMD image can be calculated using equation 4. Another point of consideration is the luminance disparity between the two eyes

$$C_D = \frac{L_I r_c}{L_I r_c + 2L_B t_c}$$

(4)

where:

C_D = contrast of HMD image (maximum)

L_I = HMD image luminance prior to combiner

L_B = background scene luminance

r_c = combiner reflectance coefficient

t_c = combiner transmittance coefficient

with the HMD on and with it off since luminance disparity has been shown to have a significant effect on scene dominance [3] . The luminance ratio can be calculated from equation 5.

$$R_L = \frac{\text{Display Eye}}{\text{Non Display Eye}}$$

$$R_L = \frac{L_I r_c + L_E t_c}{L_E t}$$

(5)

where:

R_L = luminance ratio: display eye to non-display eye

t = transmittance of uncoated combiner

The choice of a combiner coating must consider these two equations(4),(5) and must also consider the particular HMD application. There are four possible HMD situations:

Daylight viewing - symbology only

Night viewing - symbology only

Daylight viewing - imagery or imagery and symbology

Night viewing - imagery or imagery and symbology

Of all these combinations. the one that is easiest to implement and has the lowest potential of incurring difficult human integration problems is the first one; daylight viewing-symbology only. The reasons for this are:

1. Symbology presentation only requires "one gray shade" above the background luminance to be easily visible (C_D = 0.3 to 0.4 from eq. (4)) whereas imagery requires far more shades of gray to produce reasonable quality imagery (C_D = 0.8 to 0.9).

2. Since the HMD luminance can be relatively low compared to that required for imagery, the combiner transmission coefficient can be kept fairly high (low reflectance coating) and thus the luminance disparity with the HMD on or off is low.

3. Overlaying symbology on the real world scene is a compatible process and produces a reasonably integrated total scene, whereas HMD imagery tends to produce a result more like a double-exposed photograph. This effect can be minimized but the potential for binocular rivalry problems is greater with imagery than with symbology.

4. The daylight presentation tends to "wash out" any ghost images and provides a better luminance balance between the two eyes than the night situation.

A way to improve the transmittance coefficient of the combiner while still maintaining a high reflectance coefficient is to use a so-called dichroic coating that is "tuned" to have a high reflectance coefficient but for only a narrow wavelength region. By matching the coating and the primary wavelength of the image source it is possible to achieve an overall, integrated reflectance coefficient with respect to the source of 0.8 to 0.9. This is especially ideal for night viewing where the overall combiner transmittance should be kept very high. An alternative to the dichroic coating technique is the use of so-called holographic optics. This achieves basically the same end but uses holographic techniques instead of coating technology [1, pp. 275-333]. A caution with either of these techniques is that the wavelength that is highly reflected for the HMD image is also reflected from the combiner from the external world scene and is therefore not very visible looking through the combiner.

The effects of the combiner transmittance and reflectance values on the HMD MTF for daytime and nighttime viewing conditions are shown in figures 5 and 6 respectively. Four typical coating/combiner combinations were used to generate the functions shown in figures 5 and 6:

A) transmittance = 0.15
   reflectance   = 0.8
   (tinted visor with dichroic coating, integrated over wavelength)

. transmittance = 0.12
   reflectance   = 0.25
   (tinted visor with thin metallic coating)

C) transmittance = 0.9
   reflectance   = 0.8
   (clear visor with dichroic coating, integrated over wavelength)

D) transmittance = 0.92
   reflectance   = 0.8
   (clear visor with no coating)

For daytime calculations, the external luminance was presumed to be 5000 cd/m^2 and for the nighttime, 10 cd/m^2. The combined MTF of the image source and optical system was assumed to be gaussian with a standard deviation of 0.0005 of the display width. In

equation form: $MTF = C_D e^{-2(\pi\sigma f)^2}$

where:

MTF = Modulation Transfer Function
C_D = maximum PMD contrast (eq. 4)
σ = standard deviation of the point spread function ($\sigma = 0.0005$)
f = spatial frequency in cycles/display width

It is apparent from Figures 5 and 6 that the daytime conditions result in a considerably poorer display quality than the nighttime conditions.
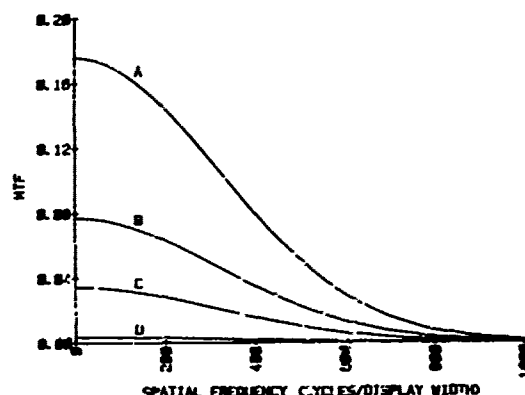

Fig. 5. Effect of typical combiner coatings on HMD MTF for daytime background luminance of 5000 cd/m^2.
A) tinted visor, dichroic coating
B) tinted visor, metallic coating
C) clear visor, dichroic coating
D) clear visor, no coating
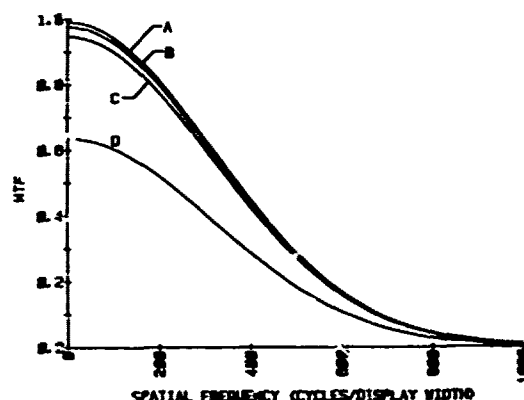
Fig. 6. Effect of typical combiner coatings on HMD MTF for nighttime background luminance of 10 cd/m^2.
A) tinted visor, dichroic coating
B) tinted visor, metallic coating
C) clear visor, dichroic coating
D) clear visor, no coating

System Transmission Efficiency

As the image is transferred from the image source to the eye some image apparent luminance is lost. Losses are incurred at each lens surface, mirror or prism surface and the combiner. The efficiency of the system is the ratio of the apparent luminance of the image as viewed through the HMD system to the luminance of the imaging source.

Safety

The HMD for airborne applications must be designed such that it will not hinder the pilot in case of emergency egress. This means that the HMD must be either easily removed from the pilot or the wires, cables, or fiber optics leading to it from the aircraft must be easily disconnected.

In the case of the miniature CRT as the image source, there is an additional problem associated with this quick disconnect requirement. The CRT typically has an anode voltage of from 5,000 to 9,000 volts. The stored charge associated with this voltage must be depleted in such a way that there is no spark at the connector as the disconnect occurs. Such a connector has been designed by Amp, Inc. and successfully underwent limited testing of its sparkless disconnect capability.

Since the primary purpose of a pilot's helmet is to afford the pilot some head protection, this capability must be preserved as the HMD is incorporated into or added to the helmet.

HMD DESIGN APPROACHES

A helmet mounted display typically consists of three sections: 1) an image source, 2) relay optics, and 3) a combiner element. Image sources are discussed in some detail in a later section. The relay optics brings the image from the image source to the viewer's eye. The combiner element, which may also be part of the relay optics, combines the HMD image with the external world scene. The optical coating on the combiner is extremely important since it determines the reflection and transmission characteristics of the combiner, which in turn determine the see-through capability and the relative luminance levels of the HMD image and external scene.

The most basic HMD optical design approach is a simple magnifier. This approach is discussed in [1] and [2]. In the design approach by Hughes Aircraft Company [11], the image source is a miniature cathode-ray tube (CRT), the relay optics is a multi-element simple magnifier and the combiner is a flat, coated beamsplitter. Figure 7 shows one of the optical designs for this approach. The HMD housing mounts to the side of the helmet at eye level. The disadvantages of this approach are relatively little eye relief, loss of peripheral vision on the HMD side and limitations on maximum achievable apparent field of view. However, this approach is simple and permits reasonably efficient (high luminance) transmission of the image from the CRT to the eye.

A second simple magnifier approach to the HMD, designed by Marconi Aviation of England [12], is shown in Fig. 8. The image source is a 20 by 23 element light emitting diode (LED) array with specialized symbols at the bottom, a prism and spherical reflector comprise relay optics with the spherical reflector also acting as the combiner element.
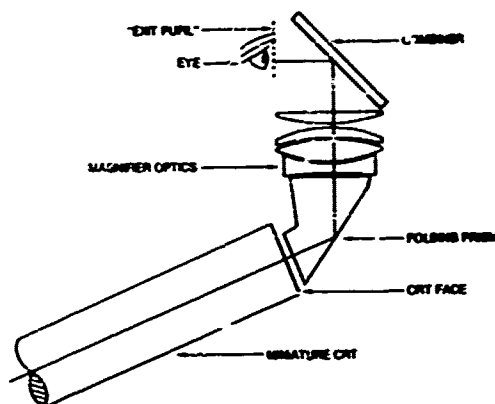
Fig. 7. Simple magnifier HMD
with flat combiner; Hughes Air-
craft, Co. Ref. [11].
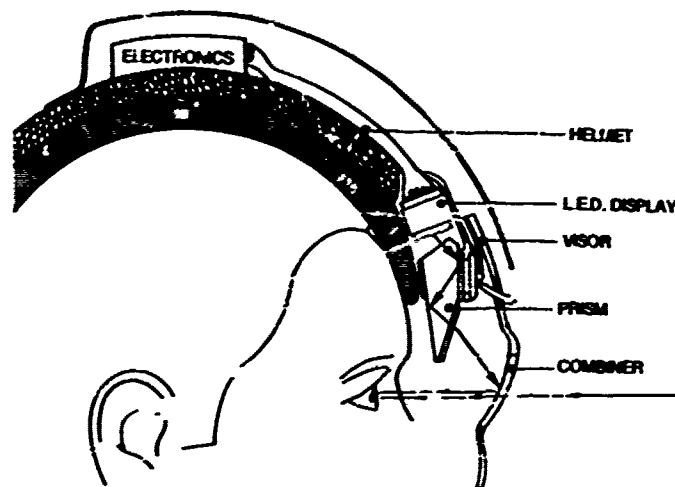
Fig. 8. Simple magnifier HMD using
LED image source and spherical combiner;
Marconi Aviation. Ref. [12].

In this version the spherical combiner is inset, at an angle, into the flight visor.
Later versions blend the combiner into the visor to form a continuous surface. The prism
relays the LED array image to the focal plane of the spherical combiner. The spherical
combiner acts as a simple magnifier and produces a virtual image of the LED array at
infinity, that is visible to the viewer. The combiner optical power is limited by the
optical distance between the combiner and the LED array since the combiner focal length
must be equal to or greater than this distance to produce a visible virtual image. When
this distance and the focal length are equal, the image appears at optical infinity; if
the focal length is greater than the optical distance then the virtual image is produced
at some finite distance from the viewer's eye. The angular field of view is related to
the magnifier optical power and the LED array format size by:

$$\theta = 2 \arctan \left(\frac{s}{2f}\right) \tag{6}$$

where
    θ = angular field of view (FOV)
    s = object size (LED array diameter)
    f = magnifier focal length

    It is apparent from equation (6) that either the format size, s, must increase or the
magnifier focal length, f, must decrease in order to increase the angular FOV. The
preceding discussion outlined the limitations of decreasing f. If the size, s, is
increased, then the prism size must be increased to prevent clipping of the image. As the
prism and LED array sizes are increased, the entire assembly becomes heavier and larger.
These same considerations affect any simple magnifier approach.
    In a strict sense, the simple magnifier optical design does not produce an exit pupil
as such. Instead, there exists a trade-off between eye relief and maximum permissible
lateral movement of the eye before 50% vignetting occurs. Equation (7) shows this rela-
tionship.

$$p = D - r\frac{s}{f} \tag{7}$$

where:
    p = pseudo exit pupil diameter
    D = useful magnifier diameter (clear aperture)
    r = eye relief distance (magnifier to eye pupil)
    s = object format size (LED array diameter)
    f = magnifier focal length
The parameter, p, corresponds to the exit pupil diameter for exit pupil forming optical
systems. To determine the maximum lateral movement of the eye that can occur before any
vignetting occurs the pupil diameter of the eye must be subtracted from "p" in equation (7).
Thus:

$$m = P - P_e = D - r\frac{s}{f} - P_e \tag{8}$$

where:
    m = maximum allowed eye movement with no vignetting
    P_e = pupil diameter of the eye

Equations (7) and (8) show that for a particular simple magnifier system, the eye relief
is reduced if the lateral movement envelop (m) is increased. Again, these two equations
apply to all simple magnifier design approaches. The Marconi Aviation spherical combiner
design produces a limited FOV display but the "exit pupil" at the typical eye position
is excellent, (see Table 3).
    A third simple magnifier approach was constructed at the Naval Weapons Center using
a holographically produced optical element as the magnifier and combiner with an incan-
descent lamp, filter and photo transparency as the image source [1, pp. 303-333]. This

device provided an image of a circular reticle to the viewer's eye. The holographic opti-
cal element is basically a complex diffraction grating (typically a reflection, phase
grating) produced by holographic techniques. One major advantage of this approach is
that the direction in which the image is diffracted from the holographic optical element
(HOE) is independent of the substrate shape or orientation. Also, for reflection phase
HOE's the reflection coefficient can be made very high for only a narrow band of wave-
lengths while the transmission coefficient can be maintained at a high level for all other
wavelengths. By using a narrow wavelength band image source, both the see-through capa-
bility and the HMD transmission efficiency can be kept at high levels. However, there are
several problem areas associated with HOE's that make them difficult to work with. While
it is true that the first order image direction is independent of the substrate shape and
orientation, the optical aberrations are not. As the substrate differs more from the
shape and location of the optical element that the HOE is imitating the optical aberra-
tions increase rapidly. Techniques for reducing this effect are being investigated with
some success. Other problems include production difficulties, materials limitations, and
design complexities. Several studies have been done in the area of holographic optical
elements [1]. Hughes Aircraft Company has successfully fabricated a wide field of view,
holographic heads-up display, but efforts to build a HOE HMD have resulted in experimental
HMD's which are bulky and possess moderate image quality.

A fourth simple magnifier design was constructed under an AFAMRL effort by Honeywell,
Inc. which produced an image of a reticle and four discrete information lights. A parabo-
loid shaped visor served as both magnifier and combiner. The image source consisted of
five miniature incandescent bulbs mounted behind a transparency of the circular reticle
and four discrete lights. This "reticle generator" was mounted above the focal point of
the paraboloid visor, just in front of the pilot's forehead. The reticle assembly was
mounted to the upper part of the visor on a spring mount such that it would flip into
position as the visor was brought down into place, and fold up as the visor was shifted to
the stored position. The apparent angular sizes of the two reticle rings were approximately
10 milliradians and 50 milliradians. The four discretes were located approximately 75
milliradians from the center of the image. The line width of the reticle rings was about
2 milliradians.

Several more complex optical design approaches have been constructed. These are
characterized by intermediate image planes that are reimaged by relay optics. The advan-
tages of this class of approach are that the image source can be mounted further from the
eye and the eye relief distance can be made larger. Typically these devices produce a
well defined exit pupil.

One of the earlier examples of this type of design was produced by Hughes Aircraft
Company [13]. The image source was a miniature CRT, the relay optics consisted of two
folding mirrors, two relay lenses, a field lens and an eye lens. Several viewers were
fabricated having various apparent FOV's. The FOV's ranged from 18.9° to 62.8° (calculated)
with a minimum exit pupil of 4mm. These HMD's had no see-through capability since no
combiner was used. The absence of a flat combiner permitted the exit pupil to be formed
closer to the last optical element and thus allowed the eye to be situated closer to the
eye lens. This small eye relief distance (14mm) and small exit pupil (4mm) were the
factors traded-off to achieve the large 62.8° FOV.

Honeywell, Inc. fabricated several HMD's that used the relayed-image optical design
approach. The Honeywell Model 7A incorporated the paraboloid visor, previously discussed,
as a key part of the optical system [11], [14], [15]. The initial version of this HMD was
the Model 6 which used a heavy glass visor to demonstrate the concept. The Model 7A used
a thin, molded plastic paraboloid visor. The image source was a miniature (25mm diameter
by 125mm length) CRT mounted horizontally at the lower rear of the helmet. The CRT image
was reflected from a folding mirror vertically upward through a relay lens to the input
face of a 750,000 element coherent fiber optic bundle (FOB). The FOB conducted the image
from the rear of the helmet to a point above the left front edge of the helmet just over
the pilot's forehead. The image formed at this surface of the FOB was focussed at infinity
(collimated) by the collimation optics. The beam of light was bent outward by a mirror and
directed to a coated area on the upper left part of the paraboloid visor. The visor
focussed the light back to a mirror located in front of the pilot's forehead producing an
intermediate image in approximately the same plane as the mirror surface. The image
reflected from the mirror to the lower right section of the visor where a reflective
coating directed the beam back to the pilot's eye. On the first bounce from the visor the
paraboloid served as half of a relay lens system and on the second bounce it served as an
eyepiece or eye lens. Figure 9 shows schematically the optical design. The numbers 1

Fig. 9. Pictorial conceptual layout of the parabolic visor HMD.
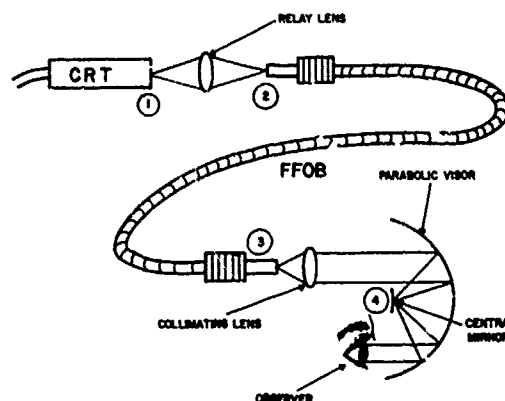
through 4 on Fig. 9 refer the image planes, at the CRT face, input and output of the FOB, and the central mirror. Note that any dust or particles collected on any of these surfaces is imaged through the system with the desired picture. The apparent angular FOV of this device was approximately 20° on diagonal with a 10mm exit pupil. The projected image produced with this technique suffered from parabolic distortion as shown in Fig. 4. The CRT drive electronics had to be modified to distort the image on the CRT in such a way as to compensate for the optically produced distortion. Also, the coating in the area of the first bounce from the paraboloid was necessarily made opaque to insure that sunlight could not accidentally be reflected down the light path to the pilot's eye.

Later versions of this approach, designated the Model 7B and Model 8, were fabricated by Honeywell. In order to improve the image quality, the CRT was moved to the top left side of the helmet and the FOB and first relay lens were eliminated. This removed the matrix structure and broken fiber blemishes of the FOB, but shifted the center of gravity of the total HMD upward and to the front. Also, the size of the HMD above the head increased significantly.

Another approach to HMD design that has been experimentally investigated by personnel at the Naval Air Development Center, the US Air Force Aeromedical Research Laboratory, Marconi Aviation, and Honeywell, Inc. is the use of a flexible fiber optics bundle (FFOB) for transmitting the source image to the helmet. The advantage of this approach is that the image source weight can be removed by mounting the source off of the helmet. However, the size and flexibility of the FFOB are adversely affected as the resolution (number of fibers) of the bundle is increased. For this reason, the optimum use of this approach is probably for applications requiring intermediate resolution levels (40,000 to 150,000 elements). This level of resolution is quite adequate for dynamic symbology such as that displayed on a heads-up display. However, it is marginal to inadequate for many sensor imagery applications (forward looking infrared, low light level television, etc.).

Table 3 shows a comparison of several of these HMD's for many of the HMD design parameters.

Table 3

Characteristics of Several Helmet Mounted Displays

	Hughes Side-Mount	Honeywell IHADSS	Honeywell Mod 8	Honeywell Mod 7A	Honeywell Mod 3	Marconi Aviation Mark IV
Weight	530 gms	410 gms	400 gms	570 gms	450 gms	230 gms
Exit Pupil	15 mm	10 mm	13mm x 16mm	15 mm	----	16 mm
Eye Relief	12-18 mm	49 mm	64 mm	50 mm	12-18 mm	64 mm
FOV	30° diag.	30° x 40° (45° diag)	20° diag.	20° diag.	40° diag.	10°
Transmission Efficiency (before combiner)	0.8	0.75	0.8 est.	0.2 est.	----	0.74
Image Source	CRT	CRT	CRT	CRT	CRT	32 x 32 LED array
Combiner Type	flat	flat	parabolic visor	parabolic visor	flat	spherical
Image Color	phosphor color (green, white, typical)	typically green P-43	typically green P-43	typically green P-43	typically green P-1, P-43	650 nm red, narrow band

HMD IMAGE SOURCES

The most basic device that has been used as an HMD image source is the incandescent light bulb. Five miniature incandescent bulbs were used in the Honeywell built Visual Target Acquisition System (VTAS) reticle generator assembly. One lamp illuminated a pair of concentric rings that constituted the sighting reticle; the other four illuminated individual status indicators positioned equally around the outer sighting ring. This pattern of reticle sighting ring plus four descrete status indicators provided the pilot with a minimum amount of information. However, when used with the helmet-mounted sight if proved to be a highly successful target acquisition aid.

Incandescent lamps have many disadvantages. Manufacturing techniques limit the degree to which lamps can be miniaturized. This limitation, coupled with size and weight concerns on the helmet form an upper limit on the complexity of display possible. Also, incandescent lamps are highly inefficient, converting most of the power consumed to heat instead of light. This heat must be dissipated rapidly enough to prevent unacceptable temperatures in the vicinity of the lamps.

Of all devices that have been tried as HMD image sources, the cathode-ray tube (CRT) is by far the most versatile and the most capable of producing a high quality image. For applications in which the helmet-mounted display (HMD) requires either high resolution or random positioning of symbology on the display, the cathode-ray tube is usually the first choice as an image source. Solid-state displays are currently promoted as lightweight, flexible, high resolution image sources of the future, but working production solid-state displays with performance comparable to a CRT are not presently available. As has been the case with the optics for HMD systems, there have been very few hardware alternatives from which the system designer can choose. Normally the designer will select hardware already available, to save time and money, and try to make it fit a particular application.

In selecting or d   c   .....j a CRT for use in a helmet mounted system there are a number of factors that shoulc .. considered. For example, the field-of-view, transmission efficiency, intended use of the optics, and the required resolution of the complete display system will determine critical CRT parameters such as active area size, maximum usable luminance, number of scan lines, MTF, large and small signal bandwidth and phosphor type. These parameters will in turn impact each of the three main components which comprise the image source subsystem: electron gun, deflection yoke, and deflection amplifier.

Helmet-Mounted CRT's in use today are typically cylindrical in shape with a length of approximately 125 millimeters, an active display surface diameter of 19 millimeters and a weight of about 110 grams. The need for good image quality helmet-mounted displays dictates that a CRT using magnetic deflection be employed. The primary reason for this is that the quality of the display is superior to that obtained with electrostatic deflection because the magnetic field does not interfere with the beam-forming process[16].   This factor permits brighter displays and clearer, more controllable spot sizes. It allows considerably more design freedom for the deflection amplifier electronics, making lower cost and more reliable designs possible. It also minimizes high voltage component stresses and shock hazards to using personnel. A major drawback for this type of miniature CRT have been the nonlinear relationship between the deflection current and the deflection of the beam (spot), which results in a phenomenon known as "pin-cushion distortion". Another drawback is the difficulty with achieving high line rates due to high coil inductance and its effect on rapid changes in deflection current ($L\frac{di}{dt}$). Pin-cushion distortion has been minimized through the use of sloped fiber-optic faceplates whose center of curvature coincides with the center of deflection. The design problem involved in achieving higher line rates using lower inductance yokes and high efficiency ferrite cores, to minimize heat build up, has been eased considerably with the advent of the power field-effect transistor.

Spot size and luminance is a function of the CRT final anode voltage that is selected, with higher acceleration voltages permitting higher luminance levels at lower beam currents and consequently smaller spot size. The present upper limit imposed by adverse radiation effects and consideration for operator safety is slightly over 10 Kilovolts. Miniature CRT's currently available have final anode voltages of 7 to 7.5 Kilovolts. Since CRT electron image, lens aberration and space charge effects can be helped significantly by using higher acceleration potentials while the required deflection current increases only as the square root of the final anode voltage, [17] it is usually desirable to maximize final anode voltage. During 1980, new CRT's with appropriately designed cathodes, electron optics and deflection coils that include higher (9 Kilovolt) acceleration potentials should appear. The increased deflection current can be handled by the new power semiconductors mentioned above. Tube performance should increase from present levels (for an active CRT faceplate area of 19mm horizontally by 14.5mm vertically) that exhibit a spot size of 16 microns at 50 ft-Lamberts, to a spot size of 14 microns at 250-400 ft-Lamberts.

The phosphor type selected is also critical to the total performance of the display system. The most popular types for helmet-mounted CRT's have been P-1, P-2, P-4, P-43, and P-44. P-43 has been the most popular choice due to its decay characteristics, narrow spectral bandwidth, relatively good phosphor efficiency and the small grain sizes that are obtainable. Using matched dichroic coatings with P-43 allows it to be operated at lower luminance levels and still preserve a reasonable contrast ratio between displayed information and the ambient scene. This maximizes the relative life of the phosphor compared to broad spectrum phosphors such as P-1 that must be operated at higher luminance levels to achieve the same apparent image luminance. One problem P-43 has is its sensitivity to "burn through". Newer phosphors such as P-53 recently developed in England with spectral characteristics similar to P-43, appear to have great potential for alleviating this problem. Resistance to "burn through" appears to be at least an order of magnitude greater. Other key characteristics of the new P-53 phosphor also appear to be similar to P-43 including the ability to obtain small grain sizes, a phosphor efficiency of 30 lumens/watt and a decay time to 10% of approximately 8-11 milliseconds.

There are three types of solid-state displays presently in use or under development. The light emitting diode (LED) array has been used successfully as an HMD image source for applications requiring symbology only. LED arrays consisting of 20 x 23 elements and 32 x 32 elements (with additional dedicated alphanumeric segments) have been fabricated and tested by Marconi Aviation in HMD's. These LED's emit a narrow band of light at about 650 nanometers producing a bright red image. This narrow spectral band makes the LED naturally compatible with dichroic coatings and diffraction optics. Also, the monochromatic red image is highly visible against many high luminance backgrounds due to the color-contrast effect. The disadvantage of the red LED is that red is used to denote danger in most man-machine systems. Using the red on the HMD may tend to reduce the association of red with danger or warning in other applications.

LED arrays produced with present technology do not have a sufficiently high element density to be used for sensor imagery presentation on the HMD. The active to total area ratio and the luminance uniformity for LED arrays are much poorer than for CRT's, although these have not shown themselves to be a problem for symbology only HMD applications.

One of two present parallel development efforts for miniature, high resolution, imaging, solid state HMD display sources utilizes the crossed electrode thin film electroluminescent (TFEL) approach. The development of an extremely high resolution TFEL display source capability specifically for helmet-mounted displays will result in a 525 line TV compatible feasibility model. The image is generated in a truly "flat panel" consisting of the thin film electroluminescent phosphor sandwiched between orthogonal electrodes at a density of 500 lines per inch. The image format of this display is 500 x 683 picture elements. This imaging substrate is connected with all of the hybrid drive electronics by means of flexible cabling. The hybrid drive electronics can therefore be folded around behind the display or follow the contour of the helmet shell. The other unique advantages of this approach are the flat panel nature and relatively simple construction of the imaging

system. One majcr question area to be addressed during development efforts is the successful interconnect at extremely high line densities. The incorporation of memory phosphor technqiues to raise the peak luminance capability of this display approach is also an area for investigation. Typical performance characteristics to date for imaging displays of this type include a peak luminance of 10-20 ft-L, the capability for a minimum of eight $\sqrt{2}$ grey shades, and a broadband orange spectral output. Incorporation of memory phosphor techniques could provide a 200-400 ft-L luminance capability. This approach represents a very low power consumption display capability.

The second parallel development effort for miniature, high resolution imaging display sources utilizes the liquid crystal-silicon approach. This effort will also result in a 525 line TV compatible feasibility model. The development of an extremely high resolution liquid crystal-silicon display source capability specifically for helmet-mounted displays will initially concentrate on a high resolution integrated display chip. The imaging area of the silicon chip consists of an array of 240 x 312 picture elements, with a MOS FET and capacitor located at each picture element site. The picture element density for this display is 588 per inch. The chip includes the integrated electronics for driving the display located around the periphery of the imaging area on the same silicon chip. This therefore represents a total of over 75,000 active elements on a single chip, which is at the leading edge in terms of the state-of-the-art of the silicon semiconductor industry. In this display, 525 line TV compatibility is achieved by displaying the second field on the same elements used to present the first field, while still maintaining a 60 Hz field rate. Since the liquid crystal display is a passive, or light modulating display approach, using the dynamic scattering effect in the liquid crystal, a light source must be incorporated into the system design. One of the unique advantages of the liquid crystal-silicon display approach is that the entire display system, including peripheral drive electronics, can be fabricated using the same processes on the same chip, thus avoiding any high density interconnect situations. The large commercial technical base and ever-increasing level of complexity in the silicon semiconductor industry certainly benefit this development. The illumination source/projection scheme inherent in this approach offers high luminance potential. Since the illumination source is chosen with overall systems considerations in mind, the spectral output of the display (both peak wavelength and bandwidth) can be tailored to be compatible with a variety of conventional and diffraction optical systems. The size and optical interface with the resulting display source "packaging" scheme must be considered in an overall system design. One major question to be addressed during development efforts is that of yield for a chip of this complexity and area. The response time associated with a liquid crystal display is, in part, inversely proportional to the thickness of the liquid crystal layer. A part of the development effort should therefore be a sufficient control of the cell thickness and uniformity of spacing over the display area to achieve a response time which is commensurate with video display rates.

Both of these solid state imaging display source approaches being pursued are line-at-a-time addressed displays. The rows of the display are sequentially addressed, and the video information for an entire line is entered and displayed at once via the columns. Both display techniques are relatively low voltage approaches. Typical operating voltages are 200 volts for the TFEL and 30 volts for the LC as compared to 7KV for the anode voltage in miniature cathode-ray tubes. Both of these approaches represent a relatively low power display capability, with typical display system power consumption under 2-5 watts. Both types of imaging display sources offer a small size, lightweight unit for system integration.

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AN ADVANCED ELECTRONIC COCKPIT INSTRUMENTATION SYSTEM:
THE COORDINATED COCKPIT DISPLAY

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SUMMARY

It will be difficult to modify current aircraft instrument panels to accommodate all new information required to operate within an increasingly complex air traffic control system. Cathode Ray Tube (CRT) and computer technologies have reached the stage where current flight and engine instruments can economically be replaced by computer-controlled CRT displays. This provides a tremendous opportunity for flexibility to the cockpit display designer, but the use of this flexibility should stay within the realities of the flight environment. This report describes one approach to the replacement of flight instruments, using three separate color CRT's. Each CRT displays information pertinent to one of the three orthogonal projections of the aircraft flight situation. Three airline pilots made a preliminary assessment of this display set. Comments, rankings, and ratings show that, in general, the pilots accepted the concept of pictorial flight displays.

INTRODUCTION

The aircraft instrumentation designer faces the prospect of designing for information requirements that will be continually changing in the future and changing increasingly in the direction of providing more information for the pilot to process. The information from new complex avionics systems, needed to operate within an increasingly complex air traffic control system, will have to be added to, combined with, or made to replace the already large array of cockpit instruments. Because the number of instruments cannot increase without limit and because current instrumentation appears to have nearly reached a saturation point, these new systems seem certain to force extensive cockpit instrumentation redesign. This paper is limited to a discussion of flight instrumentation systems; however, generalizations to engine instrumentation or other aircraft instrumentation systems are readily possible.

Opposing cockpit change are economic and operational realities of the commercial flight community. Due in large part to safety considerations, substantial changes in cockpit instrumentation cannot be imposed within short periods of time. Because airline pilots have served extensive apprenticeships using instrumentation that has changed very little in 20 yr, it would be unwise to abruptly change all cockpit instrumentation, even if the economic factor were not involved. Moreover, many years of experience with current instrumentation have led to operational procedures that are optimized in terms of those instruments.

Fortunately, there appears to be a natural solution to this seemingly contradictory need for change and the desire for stability. Cathode ray tube (CRT) and computer technology have reached the stage where replacement of flight and engine instruments with CRT and supporting computers can reduce weight while lowering first cost and maintenance costs (Ref. 1). With this new equipment, the standard instruments can simply be reproduced on the CRT's by using proper computer software. Once this is done, it will be possible to make future instrument changes by changing the computer software. The way is also open for fundamental changes in overall format if it can be shown that such changes have the advantage of making pilot interpretation easier. Such a format change can be viewed as the goal of a series of evolutionary changes.

There are two situations in which rapid assimilation of the flight situation is especially necessary. The first is the higher-than-usual workload situation in which flight conditions are changing, communication demand is high, etc. The second is the very low workload situation that is interrupted by an unexpected event. In both cases, the need is for a display set from which the current situation can quickly and easily be assessed at a glance. This display set must also furnish appropriate information for all intermediate levels of decision and control functions.

There is a variety of approaches that could be used in the design of such an easily interpretable format. This paper describes one such approach and explains how it evolved. This entire display set is called the coordinated cockpit display (CCD) because of the coordination of information among the individual CRT's. Once the basic design was complete, it was necessary to see if line pilots could use it, in executing maneuvers, and to obtain their opinions of the design. The same maneuvers were also flown with standard-type instruments for comparison. There was no strong expectation of any difference between the two for this first phase of the project. The next phase will be to implement CCD within a simulator context where pilot performance can be measured under extremely high and low workload conditions. This will be a major effort and will be integrated into other programs within the Man-Vehicle Systems Research Division (MVSRD) at Ames Research Center.

ORIGINS OF CCD

The following requirements were established as essential characteristics of any potentially feasible cockpit instrumentation system:

1. The system was to be based on sound human factors principles.
2. The system had to accept any new information that might be required for operation in the future National Airspace System without major hardware addition or redesign.

3. The system had to accept any new information that might be required for operation in the future National Airspace System without introducing clutter or logical inconsistency.

4. The system had to be acceptable to pilots trained on standard cockpit instrumentation, yet capable of evolution in accordance with criteria (2) and (3) above.

The need for the first criterion is obvious. Some of these human factors principles will be seen when the CCD is explained below. A more detailed rationale for some of the design decisions is given in Ref. 2. Criteria (2) and (3) were discussed in the Introduction. The logic used for the placement of information on the CCD takes care of much of criteria (4) by analogy with the basic "T" flight instrument arrangement. Also, a color selection scheme based on the instruments "information category" will be explained.

Basic "T"

The basic "T" (Ref. 3) instrument configuration, which is standard for virtually all civil transports, does more than merely standardize placement of instruments. In the basic "T" configuration, those instruments that present position and motion information are selected and then positioned to help the pilot visualize the situation in three dimensions. In general, the position and motion information presented on an instrument is related to the instrument's position as though the aircraft's position and motion had been projected, from the interior, onto screens composing the front, right, and bottom of a box (see Fig. i), which is then folded flat.

In the basic "T" format, the attitude instrument is placed top center, as close as possible to the pilot's out-the-window line of sight. Directly below the attitude instrument is the direction or course indicator; directly to the right of the attitude instrument is the altimeter; and directly to the left of the attitude instrument is the airspeed indicator. The attitude indicator displays information about the aircraft's motion, but not position, in a vertical plane through the wings. Hence, attitude is associated with the front of the box and so is placed top center. The altimeter displays information about the aircraft's position and the rate and direction of the pointer movement also yields an indirect indication of the aircraft's motion in a vertical plane. Hence, altitude is associated with the side of the box and so is placed top right. The course indicator displays information about the aircraft's motion in the horizontal plane. Hence, course direction is associated with the bottom of the box and so is placed bottom center. The airspeed indicator displays information about the aircraft's motion in the forward direction. This information, used in conjunction with other instruments, enables the pilot to extract information about the horizontal position of the aircraft.

By relating the side-by-side locations of the instruments to the three sides of the box, representing the three coordinate planes in space, the pilot can, presumably, more easily transfer instrument readings into the current situation in space (Ref. 3).

The above suggests that the goal of the basic "T" instruments may be taken to provide the pilot a frame of reference in space and an image of the aircraft's motion relative to it. Mechanical instruments, however, are limited in the information relationships that can be explicitly shown, and for any information relationships that are not explicitly shown, the pilot must make the effort to construct that image. As stated by Hopkins (Ref. 4), "...it is important for all crew members to have a good mental model of the aircraft situation at any time." The goal of CCD was to expand the idea of the basic "T" to a more graphic, therefore more explicit representation of the aircraft situation.

Instrument Information Categories

Air Force Manual 51-37 divides flight instruments into three categories: control, performance, and navigation instruments (Ref. 5). The control instruments reflect the aircraft's immediate response to control inputs; for example, a stick movement that results in an attitude change is first indicated on the attitude indicator. Hence, the attitude indicator is a control instrument. The performance instruments reflect the changes in the control parameters; for example, after a sustained pitch change the flight-path angle, sink rate, and airspeed assume new values. Hence, the flight-path angle, sink rate, and airspeed indicators are performance instruments. The navigation instruments indicate aircraft position relative to ground references.

There are, of course, categories of information in addition to these. Flight directors and predictors are two important ones. Neither was included in this initial evaluation because the nature of the first set of maneuvers would have made the task trivial with either of these elements. They will both be integrated into future CCD.

COORDINATED COCKPIT DISPLAY

In general, the coordinated cockpit display (CCD) flight instrumentation system can be thought of as an evolved basic "T" which more nearly achieves the goal of the basic "T" instruments. The CCD coalesced as a resolution of the need for short-term flexibility while maintaining long-term adaptability. To satisfy the needs for flexibility and adaptability, CRT's displaying line-drawn, computer-generated indicators were used. To preserve the basic "T" relationship, the CCD uses three CRT's placed in a modified "T" configuration, as shown in Fig. 2. To ensure category separation, three different colors of line-drawn indicators were used, one for each category of information.

Modified "T"

The basic "T" instruments appearing in current flight instrumentation systems also appear in CCD and in a more-or-less familiar manner. The essential difference is that position and motion information, which is implicit in standard instrumentation, has been made explicit in CCD, primarily by the use of a pictorial presentation. This pictorial format enables a higher density of information without a concomitant increase in the number of instruments a pilot must scan. The values associated with appropriate flight parameters are used by a computer to calculate the current frames of reference and the aircraft's motion relative to

them. These relationships are displayed in a pictorial format on three CRT's along with the standard information indicators, that is, attitude, altitude, etc.

Each of the three CRT's informs the pilot about the aircraft's position and motion in the particular coordinate plane most closely associated with the conventional instrument in the same respective position. Thus, "up" on the bottom CRT and "left" on the top right CRT are the directions of forward motion. These relations can be seen by comparing Figs. 1 and 3.

Because the information displayed in a particular CRT is related to the aircraft's position and motion in one of the frame of reference coordinate planes by the relative position of the CRT, each CRT instrument complex has been named for its respective plane: the CRT occupying the position of the standard attitude instrument is called the Vertical Situation Display (VSD); the CRT occupying the position of the altimeter is called the Side Vertical Situation Display (SVSD); and the CRT occupying the position of the course indicator is called the Horizontal Situation Display (HSD) (see Fig. 3).

Several of the indicators used in the CCD system are based on the use of a sequence of DME and altitude pairs to establish a theoretical flight path, called the desired flight path. The desired flight path is displayed pictorially: (1) on the VSD as a waypoint symbol, one at a time showing next waypoint; (2) on the SVSD as a portion of the graph of the altitude versus accumulated ground distance along the desired path; and (3) on the HSD as the horizontal projection of the desired flight path. The position of the aircraft relative to the desired path is also used to drive altitude and airspeed error indicators on the VSD and an expanded lateral error indicator on the HSD. The CCD system assumes that such a three-dimensional waypoint sequence will be programmed into an on-board computer during preflight preparations.

Indicator Information Categories

Each of the indicators on each of the three displays is drawn in a unique color which designates its information category. Although the three-color information-category concept as a whole is important, the three particular colors chosen were selected for technical rather than theoretical reasons.

The control indicators are displayed in red and consist of (i) aircraft symbol, (ii) potential flightpath-angle indicator, (iii) 10° pitch marks, (iv) 10° roll angle marks and indicator, and (v) horizon line. This category of indicators, the CRT's on which they appear, and their representations are shown in Fig. 4.

The performance indicators are displayed in green and consist of (vi) altitude tape and digital readout, (vii) flightpath-angle indicator, (viii) vertical-speed indicator, (ix) airspeed tape and digital readout, (x) heading tape and digital readout, (xi) turn-rate indicator, (xii) horizontal flightpath indicator, and (xiii) groundspeed and windspeed vectors. This category of indicators, the CRT's on which they appear, and their representations are shown in Fig. 5.

The navigation indicators are displayed in yellow and consist of (xiv) waypoint symbol, (xv) ground-plane dots, (xvi) altitude-error indicator, (xvii) airspeed-error indicator, (xviii) desired vertical flightpath profile, (xix) desired horizontal flightpath profile, and (xx) expanded-scale lateral-error indicator. This category of indicators, the CRT's on which they appear, and their representations are shown in Fig. 6.

The ease of making changes and of incorporating new information into this framework was demonstrated by a separate study on pilot response to windshear. The necessary information was a natural addition to the SVSD and was somewhat more difficult to interpret on the VSD.

Indicator Interpretation

Although CCD instruments are computer-drawn instruments displayed on CRT's rather than the conventional electromechanical gauges, there are no physical or conceptual differences in reading and interpreting most of them. A brief explanation of those indicators that are new or unique follows.

Indicators (ii) (potential flightpath-angle indicator, Fig. 4) and (vii) (flightpath-angle indicator, Fig. 5) constitute an energy management complex. (Indicator (ii) indicates the constant speed climb/sink angle for the current power setting and (vii) indicates the current flightpath angle.) These indicators are scaled to be read against the VSD and SVSD pitch scales. Indicators (viii) (vertical-speed indicator, Fig. 5) and (ix) (airspeed tape and digital readout, Fig. 5) are expanding tapes, lengthening or shortening as appropriate. Indicators (xiii) (groundspeed and windspeed vectors, Fig. 5) are arrows whose direction and magnitude (as numerics) reflect their respective current parameter values. Indicator (xiv) (waypoint symbol, Fig. 6) is a symbol that indicates any waypoint in space that the preprogrammed ideal flightpath should intercept. Indicator (xviii) (desired vertical-flightpath profile, Fig. 6) is a portion of an altitude versus accumulated distance profile of the preprogrammed desired flightpath. Indicator (xix) (desired horizontal flightpath profile, Fig. 6) is a horizontal projection of the flightpath, or some portion thereof, of the preprogrammed desired flightpath. Indicators (xviii) and (xix) move in relation to indicator (i) (aircraft symbol, Fig. 4); together, these indicators completely determine the aircraft's vertical position relative to ground. Indicators (xvi) (altitude-error indicator, Fig. 6) and (xvii) (airspeed-error indicator, Fig. 6) move along the altitude and airspeed tapes. They point at the current value of the preprogrammed desired flightpath. Zero error is indicated by alignment of indicators (xvi) and (xvii) opposite the tape pointer/digital readout box for altitude and airspeed, respectively. Thus, current value, desired value, and error are related and can be seen at a glance. Indicator (xx) (lateral-error indicator, Fig. 6) gives an arbitrarily expanded indication of the aircraft's lateral error relative to the preprogrammed desired flightpath. Zero error is indicated by alignment of element (xx) with element (xix).

Despite some dramatic differences from conventional instrumentation, the CCD system could be readily implemented as a series of minor adaptations of current cockpit instrumentation. The only major change necessary would be the initial replacement of current basic "T" gauge instruments, perhaps only some of

those of the copilot at first, with their CRT displayed, computer-drawn equivalents (see, e.g., Preliminary Investigations: Displays, below). Although initially wasteful of the power of computer graphics, such a procedure would have a number of advantages, not the least of which would be the accumulation of experience with airborne computer implementations.

PRELIMINARY INVESTIGATION

The primary goals of the preliminary study reported here were to refine the CCD system, to explore some variations of CCD configurations, and to obtain some idea about the differences to be expected between the CCD variants and a more-or-less conventional instrument system. Because of the preliminary nature of this study, no attempt was made to do either a balanced experimental design or to extract rigorous quantitative data.

Desired Flightpath

It was felt that a fairly difficult task would accentuate any problems with the system, so the flightpath task chosen for these studies was based on a proposed location for a STOL airport in the downtown New York City vicinity. At this proposed STOL airport, a missed approach requires a go-around path that must simultaneously (1) avoid existing reserved flight corridors (JFK and Newark airports), (2) accommodate prevailing weather conditions, and (3) return the aircraft to an approach position. Because these constraints make any go-around path quite complicated, a potential go-around loop was selected as the flightpath task. A map of the path showing target altitudes and speeds is given as Fig. 7.

The path required a steep climb-out from the decision height (DH), arriving first at the go-around waypoint (GA), and then finally completing the loop at the original starting point, waypoint (18).

Displays

Instrument configurations — In this study, two instrument formats, each with two levels of information content, were examined. The two configurations were (1) a conventional mechanical pointer and scale instrument basic "T" configuration with the mechanical course indicator replaced by a computer-generated, CRT-displayed course indicator, and (2) the CCD.

The mechanical horizontal-situation indicator on the conventional configuration was simulated on a 16.51 X 13.97 cm (6.5 X 5.5 in.) CRT. The VSD, SVSD, and HSD of the CCD were simulated on 17.7 X 17.7 cm (7 X 7 in.) CRT's. The lines and dots that made up the displays were generated by an Evans and Sutherland LDS-2, modified to drive beam-penetration color CRT's. An SEL-840 computer interfaced with the LDS-2 to calculate the display parameters. The SEL-840 also generated the aircraft dynamics, navigation, and guidance equations, and recorded the performance data.

Information content — The two different levels of information content of the conventional configuration were (1) a system approximately equivalent to conventional instrumentation systems, that is, a basic "T" instrument configuration, and (2) a system that presented additional information so that the total system information was roughly equivalent to the CCD as described above. To make the conventional configuration comparable to the CCD, the following additional information, in pointer and scale format, was incorporated: (a) identifier for the next waypoint, (b) the distance to the next waypoint, (c) an indication of bearing to the next waypoint, (d) the flightpath angle, (e) the angle of the desired descent path, (f) the potential flightpath angle, and (g) the windspeed and direction. (These items of information are referred to later in Table 1; they are identified in Table 1 by the letter designations used here.) Figure 8 shows the conventional configuration that corresponded most closely to the CCD as described above. The level configured to be comparable with a conventional basic "T" was obtained by removing indicators (d), (e), (f), and (g).

The two different levels of information content of CCD were a reduced CCD with information comparable to the first conventional system and the CCD system as described above. The reduced CCD was obtained by removing elements (ii) (potential flightpath-angle indicator, Fig. 4) and (vii) (flightpath-angle indicator, Fig. 5) from the VSD and SVSD, element (xii) (horizontal flightpath indicator, Fig. 5) from the HSD, and element (xiv) (waypoint symbol, Fig. 6) from the VSD.

Task

The simulation dynamics were a simplified set of Buffalo (STOL) dynamics. Each flight began at waypoint (18) of the desired flightpath from an altitude of 1371.6 m (4500 ft), in a trimmed attitude in level flight and at an airspeed of 92.6 m/sec (180 knots). When a change in airspeed or altitude was required between waypoints the change was linear. A 20-knot wind was inserted on approximately half of the runs. This was chosen to be a quartering headwind or tailwind from either left or right on the final approach leg. The subjects were requested to fly as close as possible to the desired flightpath, which has been described before and is illustrated in Fig. 7. Each run lasted about 13 min. The runs, rests, and longer breaks altogether required about 3 hr each day.

The chart (Fig. 7) was available to the pilots at all times. The desired airspeed, altitude, and course bearing were listed beside each waypoint on the map. (Color coding was used to enhance information discriminability). Also included on the chart, shown outside the flightpath, were nominal bank angles for the turns (zero wind values) and prompts for pitch and roll maneuvers. These DME readout-prompts were included to facilitate flying the conventional instrument system.

Subjects

The subjects for this study were three commercial airline pilots. A brief introduction to the purpose of the study, an explanation of the simulation, and a description of the task were given to each pilot before his first trial. The pilots were encouraged to experiment and get the "feel" of the aircraft, including handling qualities at various flap settings. Generally, the pilots preferred to fly the task

TABLE 1. PILOT AVERAGE RATINGS AND RANKINGS FOR FOUR INSTRUMENT DISPLAYS

| Display | | Ratings | | | | | | Rankings | | |
| | | Orientation | | Confidence | | Workload | | | | |
Configuration	Information content[a]	Overall	Segments (range)	Overall	Segments (range)	Overall	Segments (range)	DV[b]	CW[c]	TK[d]
CCD	(i)-(xx)	2	1-5	3	2-4	5	4-6.5	1[e]	1[e]	2.8
	(i)[f]	2.5	2-6	4	2.5-4.5	5.5	4-7	2	2[g]	4.3
	(iii)-(vi)									
	(viii)-(xx)									
Conventional	a-g	3	2-5	4	3-5	6	4.5-7	3	3	5.2
	a-c	3	2-5	5	3.5-6	6.5	4.5-7.5	4	4	8.2

[a]Indicators are defined in text.
[b]Deviation (DV).
[c]Crosswinds (CW).
[d]Overall task performance (TK)
[e]All pilots selected this order except where noted.
[f]Indicator (xiv) was deleted from the VSD only.
[g]One pilot rated the other three displays in the same relative order but with this configuration last.

after a few minutes rather than to explore the simulation. Each display was explained in detail when it was first presented to the pilot. Since this was an exploratory study, the pilots were free to develop their own strategy for using the information on each display to complete the assigned task. Each pilot saw the displays in a different order. The three pilots flew a total of 90 runs; 17 runs over 4 days for Pilot A, 37 runs over 7 days for Pilot B, and 36 runs over 6 days for Pilot C. Fifty-two of the runs were made using CCD (26 runs with full CCD, 26 runs with reduced CCD), and 38 of the runs were made using the conventional configuration (20 runs with maximum information and 18 runs with reduced information). Questions and comments were encouraged throughout the study, and a structured interview with a formal questionnaire was administered at the conclusion of each subject's trials.

Results

Performance data — When individual flights were analyzed it was often possible to detect some of the performance trade-offs being made by the pilot. However, consistent evidence for differences in performance due to differences in displays was meager, caused largely by changes attributable to learning. Each pilot had his own unique performance pattern. In general, however, Pilots A and C had lower airspeed and altitude errors and Pilot B had lower lateral error using the CCD format. Pilot B had about the same altitude error on both the conventional and the CCD formats. Otherwise, the pilots had lower error scores on the conventional format. Within a given display format, altitude error was less when flightpath angle was present. This trend for altitude error was present for each pilot whereas, for airspeed and lateral error, opposing pilot trends averaged out to mask any statistically significant effects.

Rating data — Three arbitrary rating scales were devised to ascertain the pilots' estimation of the utility of the instrument systems. Each of the rating scales had a minimum value of 1 and a maximum value of 10. The items that the scales measured and some approximate scale positions were (1) a degree of orientation (complete mental picture, 1, to completely disoriented, 9), (2) confidence in appropriate next control action (complete confidence, 1, to mostly uncertain, 9), and (3) the degree of workload (completely undemanding, 1, to completely demanding, 9). On their last day the pilots were asked to rate the four display alternatives considering the overall flight and also considering each waypoint to waypoint segment of the desired flightpath. The overall average values are given in Table 1 under "ratings." Also listed under "ratings" are the range of ratings given for the individual flight segments, the lower number for the easiest segment, and the higher number for the most difficult segment.

The pilots were also asked to rank-order the instrument displays on the following questions:

1. Deviations (DV): Which display would you choose if you had to suddenly deviate from the planned flightpath and then return to it?
2. Crosswinds (CW): With which display did you best cope with crosswinds?
3. Overall task performance (TK): With which display did you best perform this task? Now rate the four displays on a scale from 1 to 10, 1 being ideal, and 10 being absolutely unacceptable.

The rank order of the displays is given in Table 1 under "rankings."

Pilot comments — The appendix contains a summary of the most interesting of the pilot's comments. Because some of the results were redundant, the separate pilot comments in the appendix are a combination of daily comments, responses to direct questions, and responses given during the structured interview.

All the pilots felt their performance would have improved given more practice with the task. In particular, they felt that more experience with the flightpath angle, potential flightpath angle, and wind-information indicators would be necessary before they would be able to make full use of them. All pilots claimed a positive learning transfer across all systems, that is, they felt experience with any one system led to improved performance on all the systems.

Generally, the pilots preferred systems with more information and liked the pictorial indicators. The pilots preferred to use the SVSD when interpreting flightpath angle and potential flightpath angle; one even suggested that this information be removed from the VSD. This may be contrasted with a NASA pilot who flew the display extensively during development and program debugging; he preferred to make use of the combination on the VSD.

The pilots were asked to specify those features among all the displays which they thought were best and worst. Pilot A thought that the best feature was the side-view projection of the desired flightpath (element xviii) on the SVSD and that the worst feature was the flightpath/potential flightpath-angle complex on the VSD. Pilot B thought that the flightpath-angle (vii) on the SVSD was the best feature and that the flightpath angle on the VSD was the worst feature. Pilot C was more general and thought that the best feature was the SVSD and HSD CRT's and that the worst feature (the lack of definition and the obtrusiveness of) was the horizon line on the VSD.

CONCLUSIONS

The comments, rankings, and ratings show that, in general, the pilots accepted the concept of the pictorial systems.

The concept of drawing standard instruments on CRT's as a first step in the use of CRT displays appears to be a feasible one. The instrument HSI drawn on the CRT was accepted without question or comment.

It was observed that the pilots appeared to adopt different strategies for each of the four different configurations. This raised the warning that each step in the display evolution must be taken with care, considering the effect of new configurations on all flight regimes. The implications for training and procedures must be considered at each step.

Coupled with the favorable pilot comments about CCD, the finding of no performance differences of practical significance between the pictorial and conventional instrument systems indicates that it is worthwhile to go on to the next phase of research. The CCD pictorial approach is a promising one.

APPENDIX — PILOT COMMENTS

PILOT A

1. Easily incorporated at SVSD into his scan. He did so on his first run.
2. Found the CCD airspeed-error indicator easier to read than the error indicator on the conventional configurations.
3. Found it easier to keep track of how to get back to the desired altitude or track when using the CCD.
4. Liked indicator (vii) (flightpath-angle indicator, Fig. 5). He found it a good substitute for the VSI.
5. Had some trouble with indicator (ii) (potential flightpath-angle indicator, Fig. 4). He thought it should be selectable by pilot.
6. Thought the method of combining indicators (ii) and (vii) on the VSD gave an unwanted illusion.
7. Did not like the "off-center" position of the indicator (ii) and (vii) combination on the VSD in crosswinds.
8. Commented every day that he missed a flight director.
9. Missed having a compass rose on the CCD. He has had a "rose" for many years.
10. Had better overall inner spatial picture with the conventional configuration. He stated that, "...by necessity, (he had) to work harder at the job."

PILOT B

1. Stated (after flying CCD extensively), "(conventional configurations) seem strange after getting used to pictorial displays."
2. Stated, "Keeping mental picture on pictorials is easy, it's done for you."
3. Would prefer a conventional VSI (speaking of CCD). He had some trouble bringing indicator (viii) (vertical speed indicator, Fig. 5) into his scan pattern.
4. Would like flight-director information. He would rate CCD, with a flight director added, about two units higher than CCD as is.

PILOT C

1. Quickly adopted indicator (vii) (flightpath-angle indicator, Fig. 5) for power settings and indicator (ii) (potential flightpath-angle indicator, Fig. 4) for controlling flightpath.
2. Found indicator (vii) most useful for increasing his confidence in his control actions.
3. Spent little time scanning the HSD and SVSD. He stated that, "a glance peripherally" was all that was needed to know where he was. He stated that, "(It was) very useful."
4. Thought that indicator (vii) (vertical speed information) needed to be more centrally located (speaking of CCD).
5. Thought that indicators (ii), (vii), and (xiv) (waypoint symbol, Fig. 6) should be taken off the VSD.

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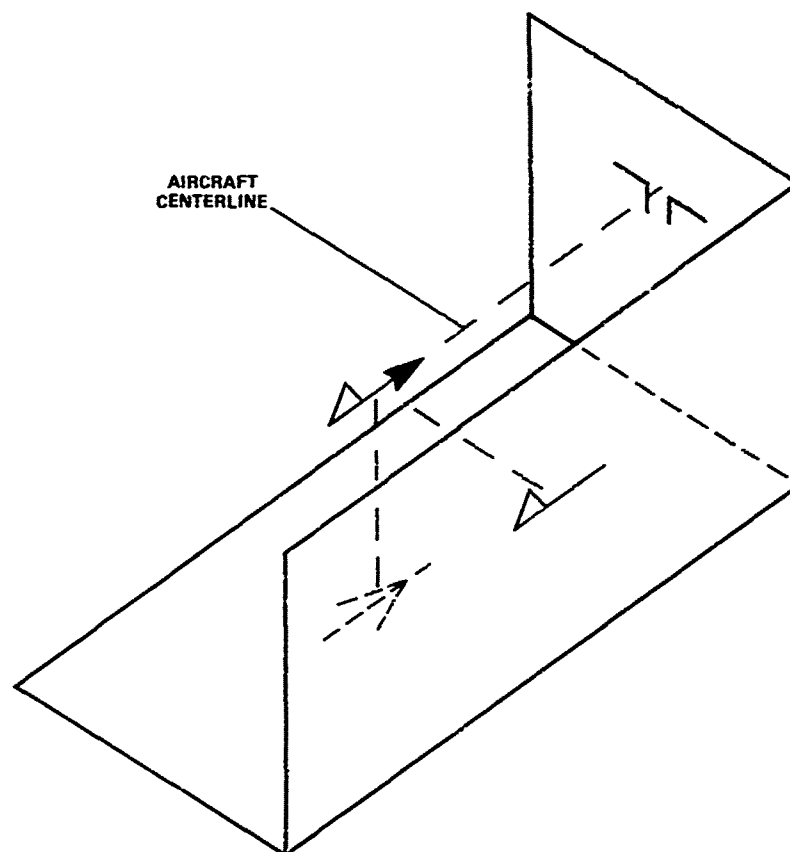
Fig. 1. Three orthogonal planes of aircraft situation.

Fig. 2. CCD in simulator.

Fig. 3. CCD.
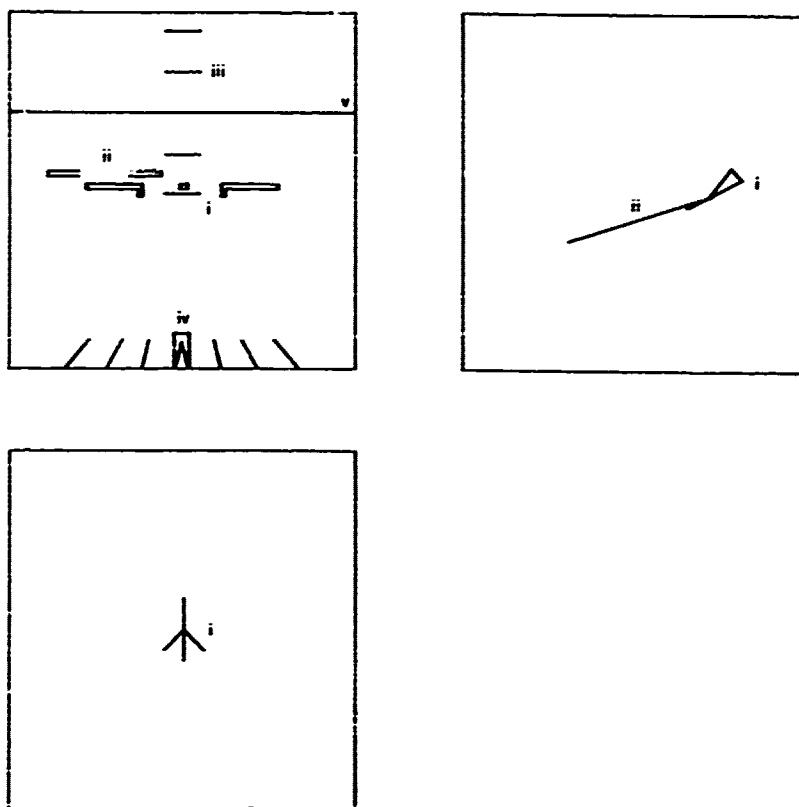
Fig. 4. Control indicators (displayed in red in CCA): (i) aircraft symbol, (ii) potential flightpath angle indicators, (iii) 10° pitch marks, (iv) 10° roll angle marks and indicator, and (v) horizon line.
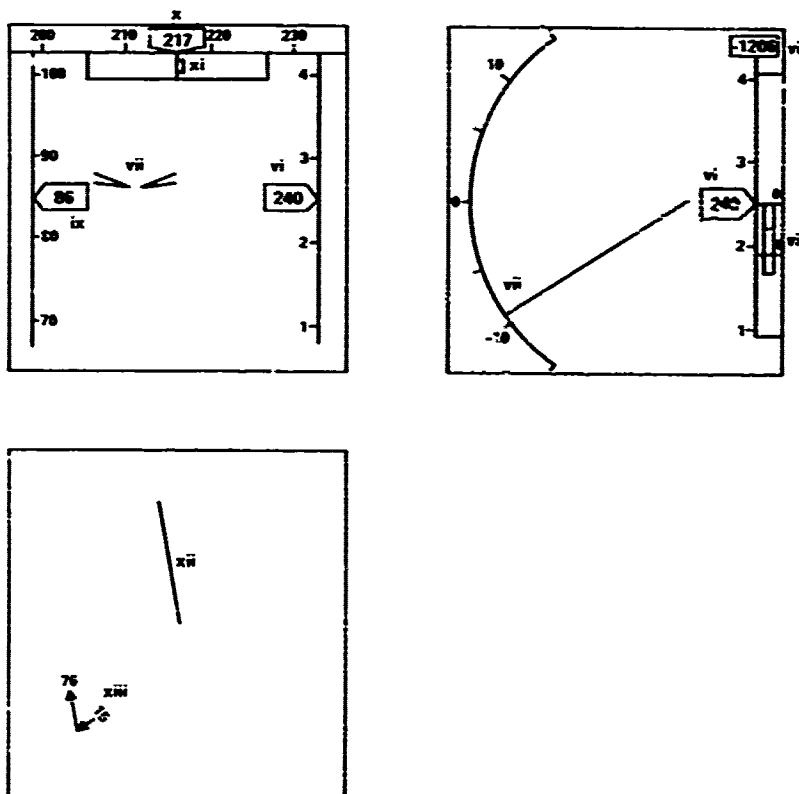
Fig. 5. Performance indicators (displayed in green): (vi) altitude tape and digital readout, (vii) flightpath angle indicators, (viii) vertical speed indicator, (ix) airspeed tape and digital readout, (x) heading tape and digital readout, (xi) turn rate indicator, (xii) horizontal flightpath indicator, (xiii) groundspeed and windspeed vectors.
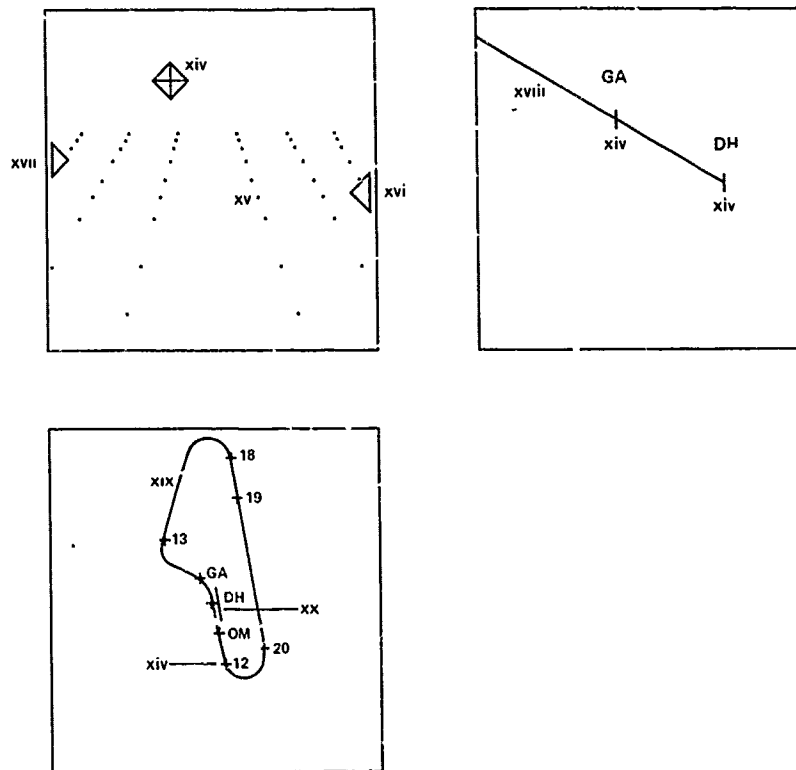
Fig. 6. Navigation indicators (displayed in yellow): (xiv) waypoint symbol, (xv) ground plane symbol, (xvi) altitude error indicator, (xvii) airspeed error indicator, (xviii) desired vertical flightpath profile, (xix) desired horizontal flightpath profile, (xx) lateral error indicator.
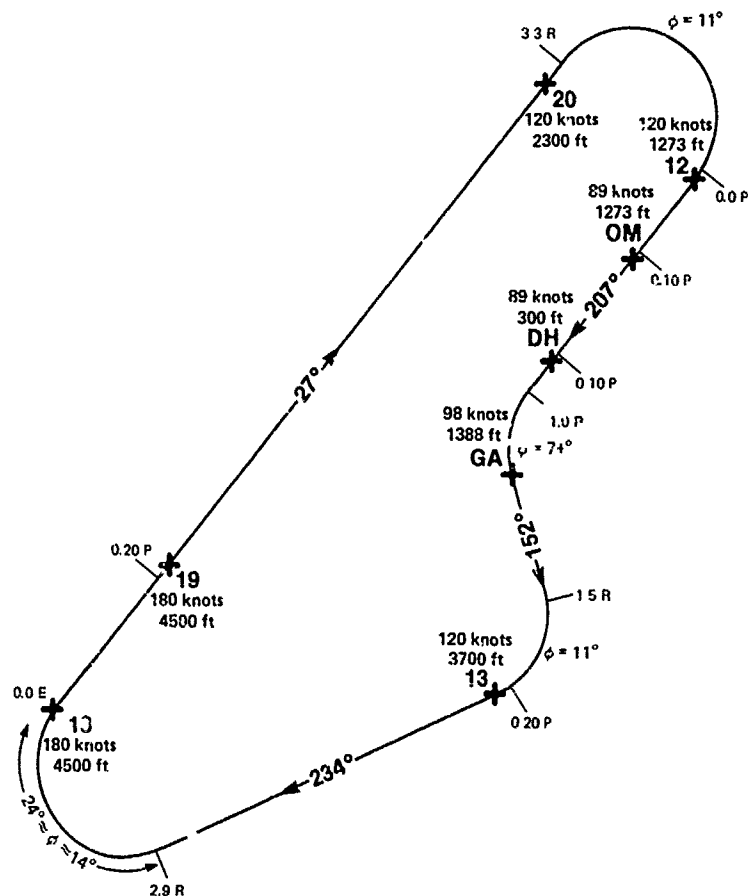
Fig. 7. Flightpath map.
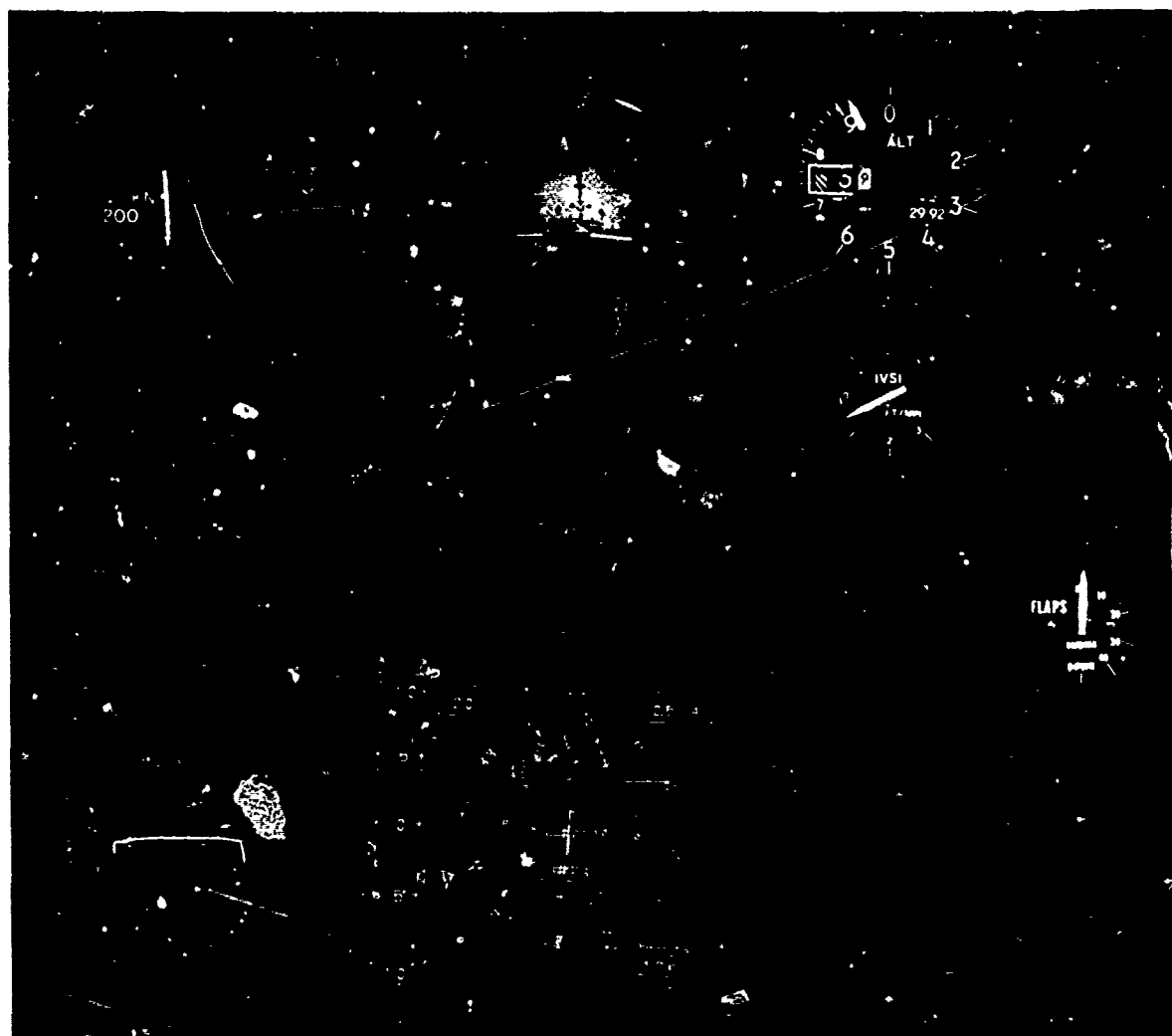
Fig. 8. Conventional instrument configuration.

THE INFLUENCE OF VISUAL REQUIREMENTS ON

THE DESIGN OF MILITARY COCKPITS

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SUMMARY

The paper discusses in a broad context the effect of visual requirements for combat aircraft with emphasis on the next generation of fighters. External vission is vital for success in air-air engagements hence the need to define canopy lines with extreme care. The criteria for doing this are discussed in some detail.

Problems of internal vision are discussed next. Cockpit display layout is considered from the point of view of moding and presentation of information as well as the more human factors problems of search. The paper concludes with an insight into the workload aspects of cockpit assessment.

1. INTRODUCTION

With current developments in aircraft performance and particularly cockpit information presentation techniques, it is becoming more apparent that the pilot is becoming the limiting factor to advancement in future military aircraft systems. Whereas in the past we have talked of manned aircraft, it might be fair to say that we are now approaching the position of aircrafted men. What makes us suggest such a change?

Over the last 15 years or so there has been a steady development in military aircraft technology part-icularly in the sphere of avionics systems. This has meant in practice that the pilot has had to cope not only with more difficult aircraft flight characteristics, largely as a result of expanding aircraft flight envelopes but more particularly with additional cockpit operational equipment such as E.O. sensors and E.C.M. devices. As aircraft have been developed to keep up with their changing operational roles so addi-tional controls associated with these new equipments have appeared in the cockpit. Only in a limited number of situations has it been possible to redesign cockpits to accommodate these new facilities, see Reference 1.1. In the majority of cases, the situation has simply been a matter of finding an additional few square inches in the cockpit, either on the instrument panel, coaming or consoles to accommodate the appropriate controls. Any considerations of ergonomics in no way enter the discussion. The practicalities of finding space dom-inate the situation.

The trend for the next generation of cockpits is to effectively replace discrete controls and dedicated instruments by electronic displays, keyboards and integrated controls. The arrival of Active Control Systems employing electronic signalling has again presented many new possibilities as well as engineering challenges. It does however, allow more precise aircraft control and relieves the pilot of dubious handling characteris-tics that certain current service aircraft possess at certain points in their flight envelopes. In cockpit terms the need for large joysticks and associated mechanical linkages is removed and mini-sticks with their associated freedom for positioning in the cockpit are now becoming common place. Arguments as to what charac-teristics such sticks should have nevertheless continue but the concept is firmly with us.

Electronic displays have been with us for a long time. The ubiquitious C.R.T. is still likely to be with us for some time. Historically it is worth recalling that the C.R.T., albeit in crude form, was with us before the first flight of the Wright Flyer. Recently, however, the fundamental change has been the development of suitable waveform generator techniques which enable virtually complete freedom for generation of information in whatever format or colour is desired. This priciple in conjunction with appropriate integrated controllers operating via data-bus concepts enables the cockpit environment to be considerably tidied up both from the point of view of space utilisation but more appropriately from an ergonomic point of view.

The acceptance on the part of the operators of such different concepts from those that have been used hithk.r to is still a topic for debate. In other spheres of engineering, e.g. A.T.C., industrial control, electronic displays have been readily received. In the civil aircraft field, the trend is distinctly towards electronic displays. (Reference 1.2, 1.3). Probably in the military field the reluctance has been on the basis of two main points. Firstly, the poor reliability of electronic displays currently in service e.g. H.U.D.'s and dedicated radar displays and secondly following from this the absolute dependence on flight information which is currently thought to be best appreciated on conventional blind flying panels.

In the layout of cockpits it is clearly the visual-considerations of the pilot's needs that are a major driving point in their design. The requirement to be able to see easily both displays and controls within the cockpit with no head movement and the necessity for good all round vision for operational reasons are the dominant design factors. What is of importance however, is not just the visual requirements but how these relate to the overall psycho-motive capability of the pilot. In considering this, we must take account of the relevant discussions and know-how available in the psychological literature. This discussion will be delayed in detail until later. It is sufficient here to describe the broader aspects of the problems.

Figure 1.1 suggests a qualitative model of the way in which the human operates in a piloting environment. The primary sensory input is visual with the eye/brain combination performing the major part particularly as regards information processing. However, as is well known other senses can readily be confused by certain aircraft manoeuvring situations. The visual factor provides the dominant one in such situations.

Perception these days is now better understood than in the era of the Gestalt psychologists. In particular, the notion of the brain as a real time Fourier analyser of both spatial and time varying inputs is now well understood, see References 1.4 and 1.5. Perceptual signals are recorded in both the short and long term memory and, depending on the situation, such signals may be acted on to manipulate the limbs for control purposes. The model indicates the feedback loops associated with the internal functioning of the pilot as well as the more microscopic effects resulting from vehicle response. Because the pilot is a biological system, he is subject to a number of factors unlike a machine. Use is made of his adaptive, learning and decision making capabilities. He does, however, suffer from limitations as regards abilities to take on a number of tasks and of course fatigue is a limiting factor.

Turning to the major concern of the present paper the visual aspects of the cockpit environment, the problem is that of relating the capability of a human visual system to the tasks in hand. Such factors as contrast thresholds, colour responses etc., are the topics of companion papers. What is of basic importance is the way in which the visual system detects appropriate stimuli. In a practical environment, both head and eye movements are used to scan the visual scene for information. For in-cockpit viewing, eye movement dominates. Out of cockpit viewing makes use of both head and eye motion. The eye scans not in a smooth fashion but by means of so called saccades or discrete angular perturbations. Normally there are some two or three saccades per second and the angular scans vary from a few minutes of arc to 15 degrees. A model of the way the eye moves is described in Reference 1.6. This suggests that the eye has a sample-data control system and operates according to a reciprocal-inervation model. This means that two muscles are employed in eye scanning, one the agonist, which shortens and pulls the eye ball and the other the antagonist which lengthens and relaxes. The parameters of interest in the real world are the angular velocities of motion and dwell time of the saccade as a function of angular scan. Figure 1.2 shows this data. It is seen that larger angular perturbations demand larger scan rates although dwell times remain constant over a large range.

Such data is invaluable to an understanding of the search process used in visual scene scanning and tasks involving attention allocation. This theme will be developed further later in this paper.

2. VISUAL CONSTRAINTS

Current studies into advanced cockpit designs has focussed attention on the fighter pilots constant need for a significant area of unobscured external view. Various studies have shown that the external view from present generation fighter/attack type aircraft is considered by the operational pilot to be less than adequate.

When the opportunity for design of a new cockpit arises we need to answer two basic questions regarding a pilots external view:-

a) What view is considered adequate for the aircraft role?

b) Can this view be provided?

This chapter attempts to

i) Identify the pilots basic visual field when encumbered by his flying kit.

ii) Define an adequate view for the aircraft role and indicate the problems of providing this view.

iii) Establish the inevitable compromise solution and compare it with present generation aircraft.

iv) Indicate the operational aspects of external pilot view.

2.1 Basic Visual Capability

Before any design or layout work is undertaken a basic understanding of the pilots visual capability is desirable. It is not intended here to explore the physiology of the eye but to describe the pilots visual field.

The ability to see and identify an object principally depends on what area of the retina the image falls. Also important for identification is whether the object is viewed monocularly or binocularly. When an observer views a point using his central or foveal vision his general capability to view further objects can be expressed as a function of that objects position, size and contrast in the visual field. If all points of constant detection are plotted together, then an irregular ring around the centre of vision is obtained. This plot for an eye is the monocular field of view. When both monocular fields of view are plotted together the central overlap is the true binocular field of view.

The visual field is limited by the mechanics of the eye, but the nose, eyebrows, cheek bones and other structures of the face account for the major limiting factors. Considering the monocular field, since the cornea is convex, light from behind can be transmitted onto a sensitive portion of the retina. Light rays as much as 104° from the optical axis can be detected. Physical features though limit this view to only the temporal field. The brow cuts off light at about 50° elevation, the nose imposes an irregular limit at $60^\circ - 70^\circ$ in the nasal direction and the cheek limits light at -80° elevation. These limits are general and are shown in Figure 2.1. The superimposed monocular fields which form the binocular field of view are shown in Figure 2.2. It is important to note that any obstruction close to the eye can significantly reduce the area of binocular vision.

Figures 2.1 and 2.2 assume that the head and eyes are at rest. With full head and eye movement the facial limitations are overcome and objects within a complete sphere can be viewed. Normally visual limits are then unimportant, for the aircraft pilot however, they are very significant. The pilot often needs to be aware of another aircraft while fixating an internal cockpit instrument. Also with the advanced aircraft being considered which can sustain high 'g' levels, it will be extremely difficult to move the head, thus fine tracking at this time will be undertaker by eye movement only.

For the piloting task colour vision is also very important. An object's position in the visual field dictates its colour. The first colours to be recognised from the grey edges of the field of view are blue and yellow, while red appears only in the centre of the field of view. This colour spread is shown in Figure 2.3 and is important when considering the high 'g' situation and the positioning of warning indicators.

The foregoing discussion describes very briefly the pilot's visual fields when not encumbered by his flying equipment. The main items of equipment which affect his view are: a) the helmet, b) the face mask.

Figure 2.4 shows this equipment.

a) The Helmet

The Helmet restricts the view in two distinct ways. Firstly its presence restricts the pilot's head mobility and thus his total visual field. This limitation is most apparent when the pilot attempts to view "past the tail." The helmet also has a tendency to lag under rapid movement forcing the head to rotate within it. The helmet may also contact various objects within the cockpit thus preventing further movement. The second major effect is to cause a blinkering of the pilot's peripheral vision. This affect is caused by the helmet wings. It is worth noting that if too much peripheral view is removed, the pilots performance will be significantly reduced.

b) The Face Mask

The mask is of importance since its obscuration is introduced within the binocular field of view and this affects detail viewing. The time when mask obscuration is a problem is when viewing the side consoles. With head movement this can be overcome but with the additional helmet weight, over long periods this causes additional pilot fatigue. The mask obscuration could become more critical with the additional NBC Nuclear, Biological and Chemical equipment, (2 hoses not one). The obscuration is caused by the cheek valves and the tension chain.

Figure 2.5 shows the typical reduction in field of view caused by the helmet/mask combination. A number of pilots have suggested that the present helmets are too heavy for the high 'g' environment and the new American light weight "form fit" helmets should be used. These helmets have reduced wings and so have an increased field of view.

2.2 Required Vision

The view available to a pilot in a particular aircraft is clearly dependent upon the geometry of the cockpit and the limits to which he can move his head and shoulders. Traditionally the external vision requirements have been influenced by the following statements:-

The U.K. AVP 970 Requirement States:-   Chapter 109 View and Clear Vision

2.2.1   The pilot shall be provided with the most extensive effective view possible. Any mounting frames or reinforcing members in the general field of view shall not exceed 2" width in order that monocular view around can be achieved.

2.3.3   The real downward view required is 11° and no aeroplane shall be produced with less. It is desirable that this limit be exceeded in practice and the following should be provided.

ii) Fighter type aeroplane 15°

2.3.3   It should be possible to see at least 4° above the horizon when the aeroplane is on a normal approach to land.

2.4.1   Adequate view shall be provided for the provisions of flight and performance of the aeroplane roles bearing in mind flight refuelling, formation flying and flight safety.

The U.S. MIL-STD-850B Requirement States:-   Chapter 5 Fighter/Attack Aircraft

5.1   Single Pilot

5.1.1   Forward Pilot Position

The vision criteria set forth in this
paragraph are applicable to the forward
pilot station:-

a) The following shall be the minimum
angles of unimpaired vision available
to the pilot from the design eye pos-
ition:-

1) 0° Azimuth at least 11° down and
10° up (Every effort should be made
to exceed 11°)

2) At 20° Azimuth, left and right 20°
down.

3) At 30° Azimuth, left and right 25°
down.

4) At 90° Azimuth, left and right 40°
down.

5) At 135° Azimuth, left and right 20°
down.

These angles are shown in Figure 2.6 along with the requirement for a canopy arch.

These statements by definition are only advisory but represent a reasonable design starting point.
Both statements advise a greater view than 11° over the nose but what angle is necessary? Due to the
aircraft dynamics and the high velocity guns presently being proposed a lead angle of 15° will be re-
quired during sustained turning dogfights. Also as retarded weapons will be used for ground attack
if view to release is required, at least 15° over the nose is needed through this will depend on speed
and altitude. Both of these requirements could be fulfilled using predictive type displays but pilots
claim "real view" at weapon release is very important. There are other basic aircraft design factors
which can influence view over the nose, these will be considered later.

Another ill defined area is that of rearward view. A number of present attack aircraft have been
shown to be deficient in rearward view. Also of the pilots sampled in discussion, 85% considered
rearward view "totally necessary" for air combat. Rearward view can be defined as the ability to view
past the right side of the fin from the left side of the cockpit and vice versa. The implications of
this on cockpit design will be discussed later.

From data available, the 40° down side view is considered adequate for the major over side task,
that of updating the nav/attack system by over flying a way point.

The external view is also influenced by a number of other items such as the position of the
canopy arch and the shape and size of the windscreen pillars. The impact of these items on the view
will be discussed later.

The above discussion can then identify the view one should aim for in an advanced fighter. This
is:-

1) Over the nose 15° or greater.

2) Over the side 40° or greater.

3) The ability to view past either side of the fin.

2.3   Design Problems of Obtaining the Required View

In the previous sections various design areas were identified as having influence on the external
view from the cockpit. These affects are now discussed in more detail:-

View over the Nose

Figure 2.7 shows the aircraft design aspects which influence view over the nose. From
the basic aircraft sizing process a maximum aircraft depth can be defined. This then
allows the design eye to be fixed. With the rearward view requirements this needs pos-
itioning above the level of the aircraft dorsal, from this position and the engine size,
a fuselage base can be fixed. From the maximum depth and eye position, using cross sec-
tional area plots a nose profile can be defined within which the required radar dish
size can be located while complying with the view over the nose requirement. The pro-
cess is not simple and needs many iterations to provide an acceptable solution. When
finally defined the cockpit transparency and structure can be identified.

In most present fighter aircraft the windscreen structure causes significant obscuration.
The British Aerospace Hawk however, uses a one piece cylindrical section forward wind-
screen. It is possible to use this type of screen for a high powered aircraft but there
are engineering problems The screen/airframe angle will need to be approximately 27°
to allow for aerodynamic rain removal, though this will not ensure removal of flies or
other large debris. Since the screen is curved a wiper is ineffective so removal fluids

and air blasts will be required. These systems however, at present are less than adequate. Also a revised U.K. bird strike requirement has been suggested which would require a thicker screen and would therefore introduce optical distortions or require costly corrective processes. It is felt that despite these problems the operational advantage of increasing the view over the nose by removal of the screen pillars should be pursued at all costs. Present design studies are still using a windscreen canopy combination as significant engineering problems exist with the F - 16 one piece type canopy. The design of the canopy arch should then be small in projected depth to allow monocular vision around it.

Forward view other than that directly over the nose is determined by the cockpit coaming and this in turn by the forward display area. Most advanced fighter designs being considered presently employ some degree of seat reclination and this has an adverse effect on display area. The use of electronic display techniques has provided the ability to "trade off" display area against external view to obtain the MIL-STD angles.

Rearward View

By placing the pilots eye above the aircraft dorsal line and extending the transparency to the dorsal, this is all that can be effectively done to provide a good rearward view. One then has to reduce factors within the cockpit which affect rearward vision. These are the width of the seat head box and the canopy.

The seat head box on some seats is larger since the parachute is installed within it. By machine packing the parachute the headbox volume could be reduced although logistic problems can occur with this type of packing.

The canopy width is an aerodynamic trade off. With sufficient width the pilot can roll his head, lift his shoulders and view behind, though this desirable feature may increase aircraft drag beyond an acceptable performance level.

Side View

With the forward and rearward view defined, the side view tends to be also defined. The only area which is worth detailed consideration is the canopy/fuselage interface.

The discussion has focussed attention on external view but a clear unobstructed view of the display and consoles is also very important.

2.4 Evaluation of External Vision

The method used to produce the visual plots for the advanced cockpit are theoretically derived. The method used is that stated in MIL-STD-850B which produces azimuth and elevation angles for plotting on an Alitoff's equal area graph.

Figure 2.8 shows the view from a projected Advanced Cockpit Mockup. For comparison, a typical modern combat aircraft is shown in Figure 2.9. Layouts such as these provoke comment by pilots in a number of areas. The major complaints being:-

Canopy arch width/position.

Forward windscreen pillars position.

Installation of instruments on the glare shield.

From Figure 2.8 it can be seen that the canopy arch is small enough to allow monocular viewing and thus reduce head movement. Due to the display console layout the coaming obscures more view than normal. This seems to be offset by the removal of the windscreen pillars. The view over the side is greater than any of the comparison aircraft.

Figure 2.10 shows the rearward view from the same cockpit. This shows that the major obscuration is caused by the fuselage and wing. This view is produced assuming the pilot has released his shoulder straps and rolled his head across the head box. Even by lifting the shoulders no significant increase in rearview can be obtained. These movements have been performed within the cockpit mock-up and proved possible though this does not mean that this is so when pulling high 'g'.

This comparison shows that the removal of the windscreen structure has a very beneficial effect on view over the nose. It is possible to place the canopy arch in a position to provide monocular view around it thus reducing its previous detrimental effect. It is also shown that greatly improved rearward view can be obtained along with adequate view over the side. These statements are based on the assessment of reported data on other aircraft.

2.5 Operational Aspects of External Vision

The fighter pilot has the fundamental need in any type of combat to know the position of targets within his external plane of reference and usually before weapon release he requires a visual verification. For an Air to Ground attack the parameters which affect the ability to achieve visual verification include:

Terrain screening,   Aircraft speed,
Weapon delivery height,   Aircraft turning capability,
Weapon type,   Type of target,
Target range,   and Meteorological conditions.

Terrain profiles of typical areas in which ground targets may be detected have been analysed to produce curves indicating the probability of a target being unmasked at a given range when viewed from a given clearance height. Typical results are shown in Figure 2.11. An analytical fit has been derived and is given by:-

$$P_{unmask} = 1 - \exp \left(-\frac{\overline{R}}{R} \right) \text{ where } \overline{R} = CH^{\frac{3}{4}} \tag{1}$$

$\overline{R}$ = mean unmask range (kilometres)

R = range (kilometres)

H = height above target (metres)

C = constant

Figure 2.12 shows the unmask range for the curves in Figure 2.14. It is clear that terrain screening is a major factor in limiting available time for target search and attack.

For an attack using conventional weapons of an off track target the 'turning' performance of the aircraft becomes a limiting factor. The use of smart weapons which can be launched with the aircraft in non turning flight considerably increases flexibility since greater manoeuvrability can be built into the missile then in the aircraft.

A typical view of the outside world as seen by the pilot at a height of 100 ft (30 m) is shown in Figure 2.13. The perspective presentation is drawn to scale and indicates the ranges and angles involved. Superimposing the range at which targets are expected to clear the terrain masking and the turn limitation curve of the aircraft (in this case 2.0 g to account for time to bank, pilot decision time and weapon forward throw), clearly indicates the narrow band in which potential targets will appear. The pilot must therefore concentrate his search in this region to maximise the probability of target detection.

This problem can be further compounded by superimposing the release limits of a retarded weapon and a forward firing autonomous guided weapon with its target marking requirements. Figure 2.14 shows these limits again presented on a perspective view from a height of 100 ft (30 m), for reference a typical target size box is also presented at 0.5 and 1 Km range.

For the initial target acquisition phase of an air-air combat the most important visual constraints are: type and size of target and the meteorological conditions. Once a contact has been established the actual sight line to the target becomes critical. Such a parameter clearly depends on both the relative aircraft performance and the tactics and starting conditions employed. Use has been made of a comprehensive digital air combat simulation programme to derive such data. A number of starting conditions were employed for 42 dogfights analysed in compiling the sight line distribution shown in Figure 2.15. This figure shows distinct regions in which a target is likely to be tracked. The forward region shows a concentration of angles from ahead to 20° azimuth and in elevation from 0° to 50° it also shows a low occurrence of sight lines beyond 60° azimuth and 80° in elevation. The rearward region has a mirror-like distribution relative to the forward quarter. An insignificant number of sightings below the tail occur.

Another factor which is of interest is the sight line rotation of the target during combat. Processing the data derived from the above mentioned 42 dogfight simulations yields the distribution shown in Figure 2.16. The histogram derived from 1,000 samples shows a significant positive skew. The mode occurs at a rotation rate of 5°/sec. It should be noted however, that rates of up to 30°/sec have been observed. This data is of interest when considering the possible use of Helmet Mounted Sights for target sighting and tracking.

3. DISPLAY CONSIDERATIONS

Since the early days of flight the answer to the increasing sophistication of ground defences and the requirements for increased mission effectiveness has been to increase the displays and controls within the cockpit. Figure 3.1 illustrates this near exponential growth of cockpit displays. If this trend were to proceed unchecked it becomes inevitable (if it were not already the case) that the pilot would be literally saturated by the number of displays confronting him. This has led to attempts being made to rationalise display system design by the introduction of cathode ray tubes (CRT) in current aircraft such as the F18 Hornet, with the likelihood of still further reduction possible.

The change to these more advanced display techniques led to a number of new design problems which require consideration, including:-

    i) How and what data should be displayed?

    ii) Ergonomic design criteria?

    iii) Controllers.

3.1 Display Moding

It is considered logical to present only the essential flight information for any phase of flight in context and in a format easily interpreted by the pilot. This rationalisation of aircraft data requires an analysis of all system information requirement both for the pilot and the aircraft. The analysis requires the development of a functional flow diagram, an example of which is shown in Figure 3.2.

This logically splits the mission into manageable discrete phases of flight. These basic events can then be expanded to show all the functions and options available during any particular event.

Using the functions described in the flow diagram an analysis is then made of the information and action requirements for the total system, an example of this is shown in Figure 3.2. This analysis provides the identification of parameters which will require presentation to the pilot during the various flight phases but does not define how the parameters are to be presented.

The pilot basically requires 3 types of data presentation to enable him to fly the aircraft, these are:-

a) Quantitative Information - from which the pilot obtains the actual value of some variables for example, fuel contents, speed etc. This information in general is suited for presentation to the pilot in digital form.

b) Qualitative Information - from which the pilot obtains the rate of change or trend of a value such variables are the rate of climb or vertical speed and attitude. This type of data is generally presented in an analogue form.

c) Status and Warning Information - from which the pilot would identify the specific status or condition of some system/components, for example the centralised warning panel. This data is typically presented as an 'on' light or as a flag on an instrument.

Each of the parameters previously defined can be classified into one or other of the groups defined above, this leads to a need to understand where the optimum location for the display of the data would be.

Generally displays presenting data relating to flight control and target acquisition are best located within the pilots near peripheral field of view. In present day cockpits the main occupant of the central panel is the Head Up Display (HUD) which presents flight and weapon aiming related data. Figure 3.3 shows the Jaguar GR Mk. 1 in which the HUD can be seen with the associated HUD controls and optics below the collimator glass. Other displays for map-target imaging and aircraft systems are located to one side low down in the cockpit. When viewing such displays the ability to continue flying the aircraft with any degree of precision diminishes rapidly. It is only when the imaging displays are physically close to the HUD that both good detection capability with the display and good tracking with the HUD becomes possible. These general considerations led to the desirability of an integrated HUD/general purpose display unit (Head Level Display) with remote display controls.

There still exists the need for the more usual cockpit information such an engine parameters, communications, frequencies etc. Here a knowledge of priority of information is required. Generally a large proportion of the currently displayed information in the cockpit is only of use when a malfunction occurs. The pilot could normally be satisfied with a simple yes/no status indication that the parameters are within tolerance. This requirement suggests the need for multi purpose tabular displays and not necessarily directly in front of the pilot since priority is low. From the information analysis it is obvious that two such displays would be advantageous, this also provides increased system integrity and data availability.

From this rationale the display system layout shown in Figure 3.4 has been developed. This figure also shows a typical data presentation (this being the Cruise Mode): Figure 3.5 describes in more detail the data presentation on each of the display surfaces.

3.2 Display Search Times

In the cockpit environment, a fundamental is that of extracting data from the displays and instruments. Important factors are the time and accuracy to extract the presented data. The implications of these parameters on the overall pilot loading will be discussed later.

Future military cockpits will contain a greater number of CRT's with a corresponding lower dominance of the conventional instruments we have seen for many years. State-of-art cockpits make use of both types of information presentation. By the 1990's however, it is expected that the electronics display, in one form or another, will be almost exclusively used. Their flexibility of operation will mean that a single display surface is likely to assume a number of formats during a given mission. The selection of formats for moding is a specialised topic in its own right.

The cockpit display tasks can be identified. The first is the extraction of numerical type data from the display. The second relates more to searching displays of real time video pictures of some target scenes e.g. detecting tasks against vegetation type background. To give some indication of the problem involved, a semi-empirical approach is adapted here, relating theoretical models to existing data.

Consider first the problem of searching a display for small targets in a cluttered background. The major problem is detecting possible targets at ranges sufficient to enable them to be overflown or attacked depending on the mission requirements. Inevitably the required targets are physically small and of low contrast at typical terrain unmask ranges. Additionally the cluttered nature of terrain images can lead to the confusion of the desired target with other similar natural or man-made features. This leads to long decision times on the part of the operator in view of the large amount of presented information.

Two factors need to be considered in some detail in studying the search problem. The first is the mean time to find a target taking account of the parameters involved. The second is the distribution of search times since large operator variability occurs in practice. Reference 3.1 presents

a body of experimental data involving the systematic variation of target contrast and size. Unfortunately the study was restricted to single targets viewed against plain backgrounds and hence direct applicability to the present problem is limited. Two results stemmed from this work. Firstly the mean time to find a target increases linearly to a first order with the display size and secondly the search time distribution is approximately exponential. An interpretation of these results in terms of Visual Lobe Theory is presented in Reference 3.2. In this theory the eye is assumed to be capable of detecting a target within an angular radius whose magnitude is determined by the target size, contrast and ambient light conditions. Outside this radius no detection is assumed to occur.

Additional to this, the eye is assumed to search a scene in a random fashion of glimpses, each lasting about 0.3 seconds.

A real scene, in contrast to the experiments normally undertaken, has a structured nature and as already noted, is cluttered by target like objects. It is here hypothesised that as the eye scans the scene, the size of the visual lobe fluctuates. The question to be answered is: What is the distribution of its size and how does this effect the search time distribution? We shall assume here that the fluctuation follows a Gamma distribution since this can be readily fitted to experimental data and satisfies the intuitive requirement of possessing positive skew:

$$P(\omega) = \frac{r^r}{\Gamma(r)} \frac{1}{\bar{\omega}} \left(\frac{\omega}{\bar{\omega}}\right)^{r-1} \exp\left(- r\frac{\omega}{\bar{\omega}}\right)$$
(2)

Following the results of Reference 3.1, the exponential search time distribution is, conditional on

$$P(t/\omega) = \frac{1}{\bar{T}(\omega)} \exp\left[-\frac{t}{\bar{T}(\omega)}\right]$$
(3)

Combining these distributions gives

$$P(t) = \int_0^\infty P(t/\omega) \, P(\omega) \, d\omega$$
(4)

which on evaluation yields in cumulative form

$$P(t<T) = 1 - \frac{1}{\left(1 + \frac{1}{r}\frac{T}{\bar{T}}\right)^r}$$
(5)

This is a general search time distribution of wide applicability.

An evaluation of equation (5) is shown in Figure 3.6. When r is infinity, the usual exponential curve results. When r = 1 a very good fit to the accumulated search data of Reference 3.1 is achieved, see Figure 3.7.

Equation (5) also shows negative values of r which indicate a less random search. The case r = -1 for example describes perfect systematic searching.

For the multi-target environment, we take m - fold convolution of the exponential distribution equation (2) noting that to a first order the mean target search time is

$$\bar{T} = \frac{\Omega}{\omega} tf$$
(6)

This gives

$$P(T/\ ) = \left(\frac{m\omega}{tf\Omega}\right)^m \frac{t^{m-1}}{(m)} \exp\left(\frac{-m\omega t}{tf\Omega}\right)$$
(7)

Evaluating as before using equation (4), we obtain for m → ∞ i.e. , a highly cluttered scene.

$$P(t<T) = \frac{1}{\Gamma(r)} \int_{r\frac{\bar{T}}{\bar{T}}}^\infty u^{r-1} e^{-u} \, du$$
(8)

This is simply the Incomplete Gamma Function.

A fundamental factor in all search problems is the limited resolution capability of the eye. This is entirely a function of its physiological make-up and is largley determined by the density of its basic resolution elements, namely the rods and cones which form the retina. As with all optical systems, the visual acuity of the eye is determined by the size of the rods and cones and the focal length of the optical system. Since the density of these resolution elements decreases away from the eye's optical axis, acuity also varies rapidly wi   ncreased angle off the so called central or foveal region. It turns out that to a first order, th   - solution of the eye is linear with angle and given by

$$\theta_R = 0.6 + 0.33\theta$$
(9)

where θ_t is in minutes of arc, and θ, the angle off the fovea is in degrees. This relationship is applicable for reasonably bright viewing conditions. In very low light the eye's acuity can diminish considerably.

A further question which needs to be answered is how big should the target be relative to the resolution of the sensor in order to enable recognition to take place. Reference 3.3 presents results of an experimental investigation into the chance of recognising small armoured vehicles as a function of the number of resolution elements N covered by the target image. It turns out that the results can best be fitted with a Weibull distribution as follows:

$$P_R = 1 - \exp(-0.08\ N^{1.4}) \tag{10}$$

where P_R is the recognition probability. Since N is simply the target size θ, divided by the sensor resolution, in our case the eye, equation (10) can be written using equation (9).

$$P_R = 1 - \exp\left(0.08\ \left(\frac{\theta t}{0.6 + 0.33\theta}\right)^{1.4}\right) \tag{11}$$

For a display having a limited number of resolution elements which is generally the case, then it is not the eye which is the limiting factor for target resolution in foveal viewing but the sensor and/or display. In this case the denominator of the exponent term in equation (11) should be replaced by angular display resolution.

Even though the target is sufficiently large to be recognised it may be that the contrast threshold of the eye is not exceeded in which case recognition cannot take place. Again this problem is statistical in nature. From experimental results, the probability of exceeding the threshold contrast C_{th} with a target image on contrast C is described adequately by a Fermi distribution.

$$P_{th} = \frac{1}{1 + \exp\left(-4\ (\frac{C}{C_{th}} -1)\right)} \tag{12}$$

Threshold contrasts of the eye have been a large research topic for a number of years and many investigations have been reported in the literature. For the present exercise use has been made of the relationships presented in Reference 3.4., suitably adjusted to describe structured search fields. Contrast thresholds vary with the angle off the foveal axis according to the relationships:

$$C_T = 9.5\theta^{\frac{1}{2}} + 87.5\frac{\theta}{\theta_t^2}\ ,\ \theta: 0.8° \tag{13}$$

$$C_T = 8.5 + \frac{70}{\theta t^2}\ ,\ \theta < 0.8°$$

A further effect which has to be modelled is the ability of the observer to distinguish the target against display noise. If SN is the display signal to noise ratio, the probability of detection PSN is given again to a first order by the Fermi distribution.

$$P_{SN} = \frac{1}{1 + \exp\ -1.636\ (SN - 3.2)} \tag{14}$$

This equation is an empirical fit to experimental data of Reference 3.5.

The three probabilities described above P_R, P_{TH} and P_{SN} when combined are sufficient to describe the detection process of a target in a single glimpse on the display relative to the target known? In practice the eye does not search a display in a uniform way but in a discrete fashion of glimpses each lasting around 0.3 seconds. The movement between successive glimpses known as saccades is so rapid as to be negligible compared with the dwell period of glimpse.

It is known from studies using eye-point-of-regard techniques that the density of glimpses on a display is not uniform. In fact, relative to the display centre the probability density distribution has positive skew and can be adequately modelled by a Rayleigh distribution. That this particular distribution is applicable is hardly surprising in view of the fact that the search process resembles the 'random walk' problem which itself is described by a Rayleigh distribution. The fact that the Rayleigh curve has a long tail means that some glimpses fall outside the display area. It so happens that the mode of the distribution occurs at one half of the display radius. This is demonstrated in the experimental results available in Reference 3.6.

On the whole, the display is searched equally likely in a circumferential manner. The probability of glimpsing an element of the display of size $d\theta$ is given by

$$P=4\ \frac{\phi}{\phi_D^2}\ \exp\left[-2\ \frac{\phi^2}{\phi_D^2}\right]\phi\ d\phi\ \frac{2}{\phi_D} \tag{15}$$

where ϕ_D is the display angular radius.

A program was written to compute the target detection probability averaged over the search distribution. This involved specifying the position of the target on the display i.e. its distance from the display centre and computing the detection probability from each possible glimpse position relative

to the target. Weighting this by the probability of the glimpse occurring in that position and summing for all glimpse positions yields an average target detection probability, Pd. The average time to find the target is given by the glimpse time t_f divided by Pd.

In Figure 3.8 the effect of display size is investigated. It is seen that, as the display area is increased, the search time increases approximately linearly, at least for the combination of parameters chosen. Higher contrast targets, as expected, are detected in shorter time. An interesting feature of this model is the prediction of a significant search time even for small display sizes. This only occurs for low contrast targets and results from the target contrast not sufficiently exceeding the threshold level. Such effects have been observed in practice, Reference 3.1 but not previously explained in this way. Figure 3.9 indicates the effect of target size on search time and quite clearly indicates desirability of having the target at least 20 min. arc on the display otherwise the search time becomes prohibitive. A larger display leads to correspondingly longer search times. These results agree qualitatively with the experimental results of Reference 3.7. Figure 3.10 demonstrates the influence of target position on the search time. For high contrast targets, search times are low and the effect of target position is of little consequence. This is a result of the parafoveal detection capability of the eye. As the target contrast is lowered, then the search times vary significantly with target position. Minimum search time occurs for the target located approximately half the radius from the display centre. This general shape of curve has been found in the experimental studies outlined in Reference 3.8.

A final problem of some significance is the optimisation of display size. Given that the target occupies a certain fraction of the display area, what is the size of display which minimises the search time? Results are presented in Figure 3.11 for two target contrast levels. It is seen that there is indeed an optimum size of display and as long as this is greater than about 10° angular subtence search times are reasonably short.

In considering the detection and read times of α numeric data, the problem is comparable though by no means identical with the real time display search problem. Since formats are chosen supposedly for clarity and the approximate position of required data is known it cannot be assumed that the display is fully cluttered or search is entirely random.

On this basis therefore, one would expect the search time distribution to depart somewhat from the usually assumed exponential shape. Some experimental data has been derived from evaluation of the civil flight deck. The tasks involved reading specified items of data from α numeric formats. The times to read out various data from the initial stimulus are shown in Figure 3.12. An adequate empirical fit is a Rayleigh distribution.

3.3 Workload Implications

In considering the visual aspects of aircraft piloting, as pointed out in the Introduction, these cannot be removed from the mental and physical actions. Although the visual sensory system is the most significant channel through which information is absorbed, other senses play their part too. These are mainly the vestibular system governing orientation and of course audio inputs.

To put the visual problem into perspective, an overall assessment of the pilot's capability is needed and this in the broadest terms can be considered as pilot workload. Despite many attempts over a number of years, particularly since World War II, no precise definition of the term workload has been arrived at, though on an every day basis, the problem is well appreciated. To attempt some sort of quantitative approach, definitions have to be made. Detailed studies of the implications of a number of factors have been reported of which Reference 3.10 gives a very good up-to-date summary. In the work reported here, an attempt will be made to cover the topic from a heuristic point of view without attempting to cover or explain the finer academic points. These are left to psychology literature.

The everyday interpretation of workload is simply having a lot to do and a short time to do it in. Implicit in this is the demand task wise made on the human coupled with the effort and time involved in completing these tasks. It is thus logical even for the cockpit environment to establish this time based model. One way of presenting the basic problem is shown in Figure 3.13. Here we indicate a number of tasks being presented to the pilot. In reality, these could include such items as manoeuvring the aircraft, operating a communication set, inserting data on a keyboard etc. Tasks can be repetitive requiring intermittent attention or apparently continuous depending on their nature. There is a body of experimental evidence existing which supports the notion that the human handles tasks in a sampling fashion, even continuous tasks. If there is a multiplicity of tasks to undertake together then the human tends to allocate attention to these tasks scanning from one to the other. The dwell time of the sample is essentially a function of the task difficulty and the repetition rate of sampling is a function of the time varying properties of the tasks.

From this simplified assessment of the situation we arrive at an index of activity for the pilot which is simply:

$$F = \sum_{i=1}^{n} \frac{Td_i}{Ts_i} \qquad (16)$$

where Tdi is the dwell time on task i and Tsi, the sampling interval. If F approaches unity then clearly the pilot is approaching an overload situation. The problem in practice is trying to apply this notion to a practical cockpit situation.

A more detailed exposition of the applicability of such analyses to cockpit design is given in Reference 3.11. Tasks need to be broken down into continuous tasks and intermittent areas. The former implies mainly aircraft flight characteristics though hand controller operations for weapon aiming also come into this category. Switching operations such as communications or weapon firing coming into

intermittent category and generally rank as secondary tasks.

In control tasks, the difficulty depends on the precision of control to be achieved and the order of dynamics being controlled. With modern Active Control Systems there is significant improvement in the precision of control - so called manoeuvre demand and a consequent reduction in pilot effort. Continuous tasks are handled by an operator in a sampled fashion, the dwell time Td dependent on the task difficulty and the sampling interval Ts dependent on the bandwidth of the input signals.

Switching tasks being secondary in nature demand division of attention, both mental and visual with a consequent loss of performance on the main control task. The dwell times on the task including arm movement are more readily determined from cockpit action studies.

From an analysis of the tasks at any one instant in a mission, it is possible to assess the degree of involvement of the pilot in flying the aircraft and hence attempt to broadly quantify the workload index. To do this in detail requires techniques outside the scope of the present paper. Topics which need to be covered are pilot psycho-motive capability, adaptation, fatigue, vehicle dynamics, control accuracy. number and difficulty of additional tasks.

By way of illustration within the framework of the current study topic the pilot's reaction time to visual stimuli in the peripheral field will be considered. Such data is of basic use in the understanding of response to changes of information status displayed within the cockpit while the pilot continues to view through the HUD. Reference 3.12 reports an appropriate experimental data. It has been found that a good theoretical model for this data is based on the equation for the Ovals of Cassini. The fundamental equation in R, θ co-ordinate is

$$R = \left[\cos 2\theta + \left\{ \cos^2 2\theta + (K^4 - 1) \right\}^{\frac{1}{2}} \right]^{\frac{1}{2}} \qquad (17)$$

The constant K defines the value of reaction time. R is the normalised angle off axis measured from the fovea. Typical contours of constant reaction times are shown in Figure 3.14. Off axis it is seen that reaction time increases significantly. The employment of this model to describe the data implies that the overall reaction time of the sensory/data processing system is the geometric mean of each individual eye's reaction time.

4. CONCLUSIONS

The paper has attempted to look at the relevance of visual problems to cockpit design in the broadest sense. It has been emphasised that to gain a full appreciation of the pilot's difficulties and capabilities in the cockpit environment, a good deal more than just visual aspects need to be considered. Hence emphasis has been placed on concept of an overall model of the way in which a pilot is considered to operate. The present paper is not the appropriate context in which to dwell on the more mathematical aspects of the pilot model. Suffice it to say that a more comprehensive understanding of human psycho-motive capability has been gained than apparent from the scattered results available in the psychology literature.

The influence of factors external to the cockpit have been discussed in relation to visual problems. In particular, viewing angles in both air-to-air and air-ground missions have been discussed. The more general problem of vision from the cockpit has been dwelt on at length and typical existing and projected aircraft designs have been discussed. Basic design problems such as canopy arches and seat design have been discussed as well as the more immediate effects of helmet obscuration.

Within cockpit viewing is discussed next. The major factors here are the influence of electronic displays and the possibilities these present for future military aircraft. An indication of how these can be moded to clean up the cockpit environment is given followed by a discussion of the ever present problem of display search and extraction of appropriate data. The paper concludes with an outline of one approach to assess overall workload in the cockpit environment.

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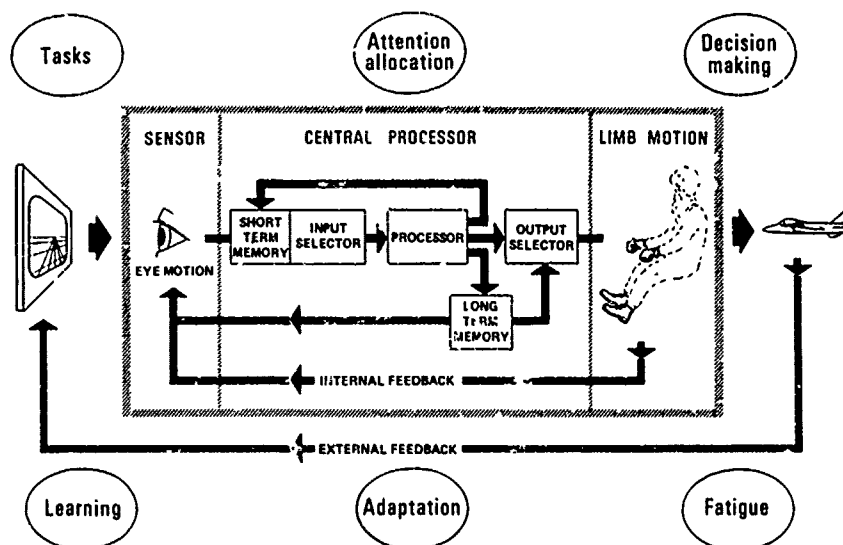
Figure 1.1   HUMAN OPERATOR MODEL
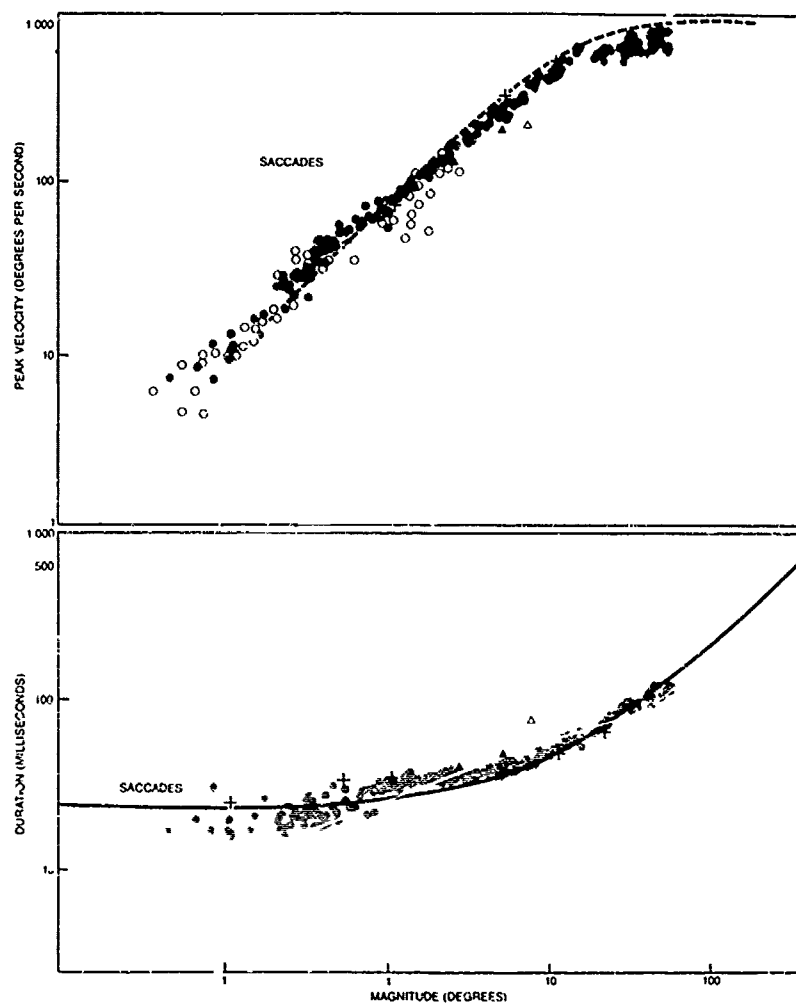
Figure 1.2   EYE SCANNING
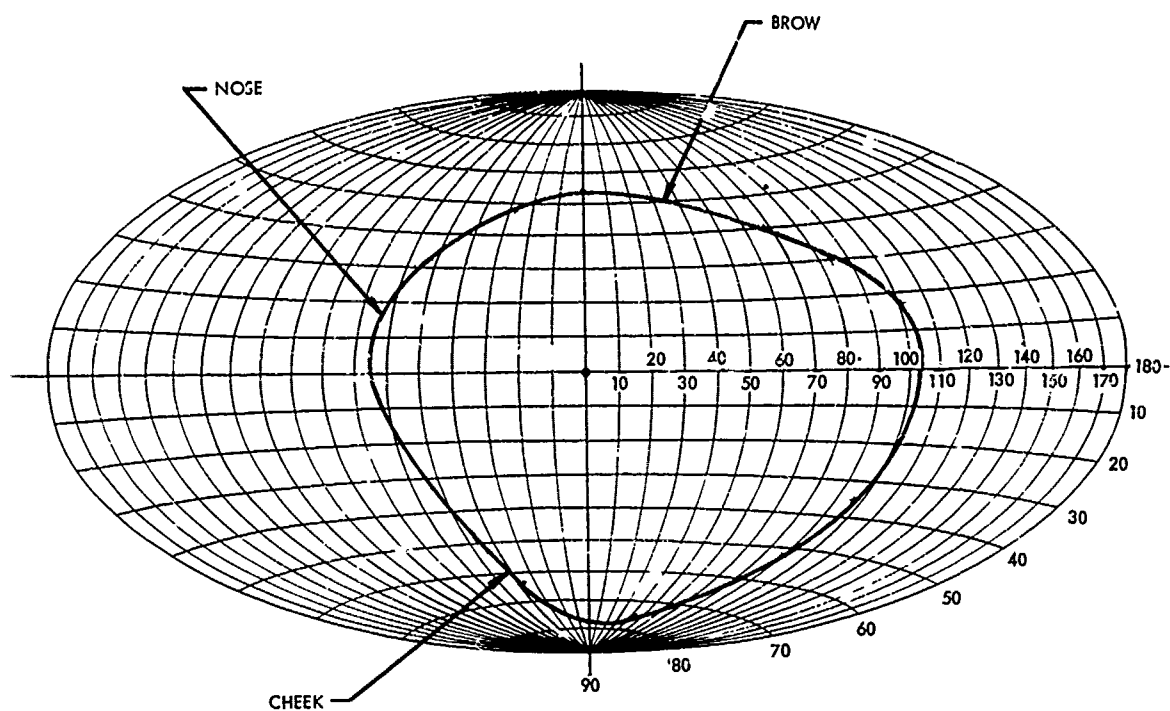
Figure 2.1   VISUAL LIMITS OF THE RIGHT EYE
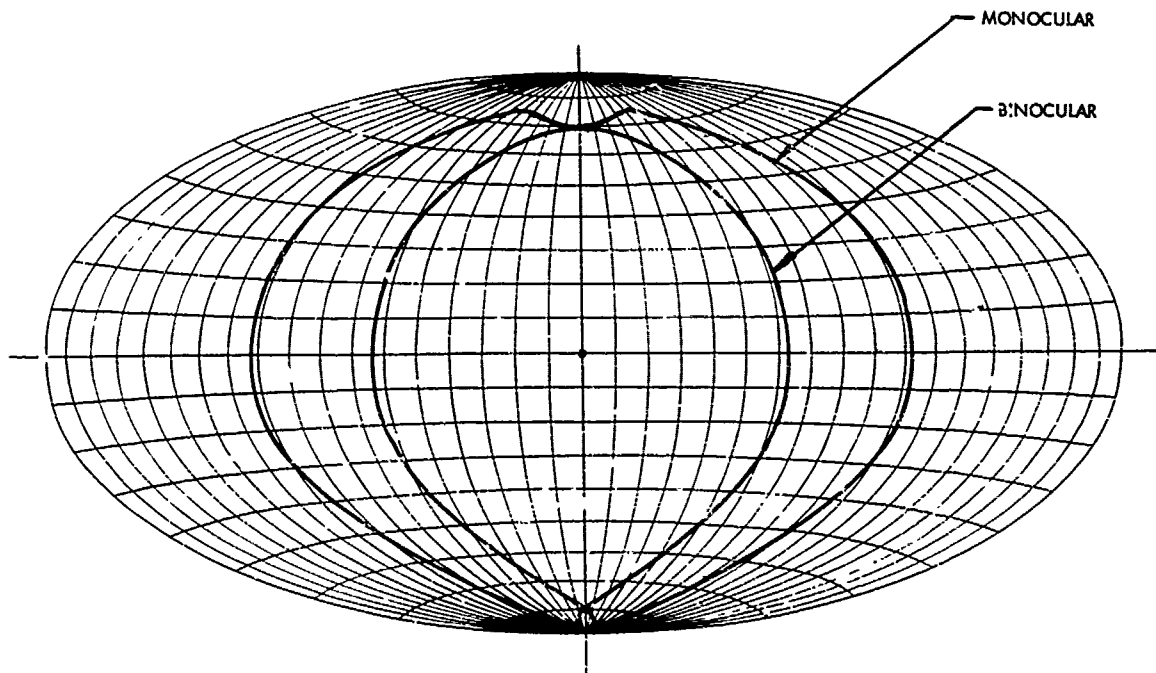
Figure 2.2   FIXATED MONOCULAR AND BINOCULAR FIELDS OF VIEW

BLUE

RED
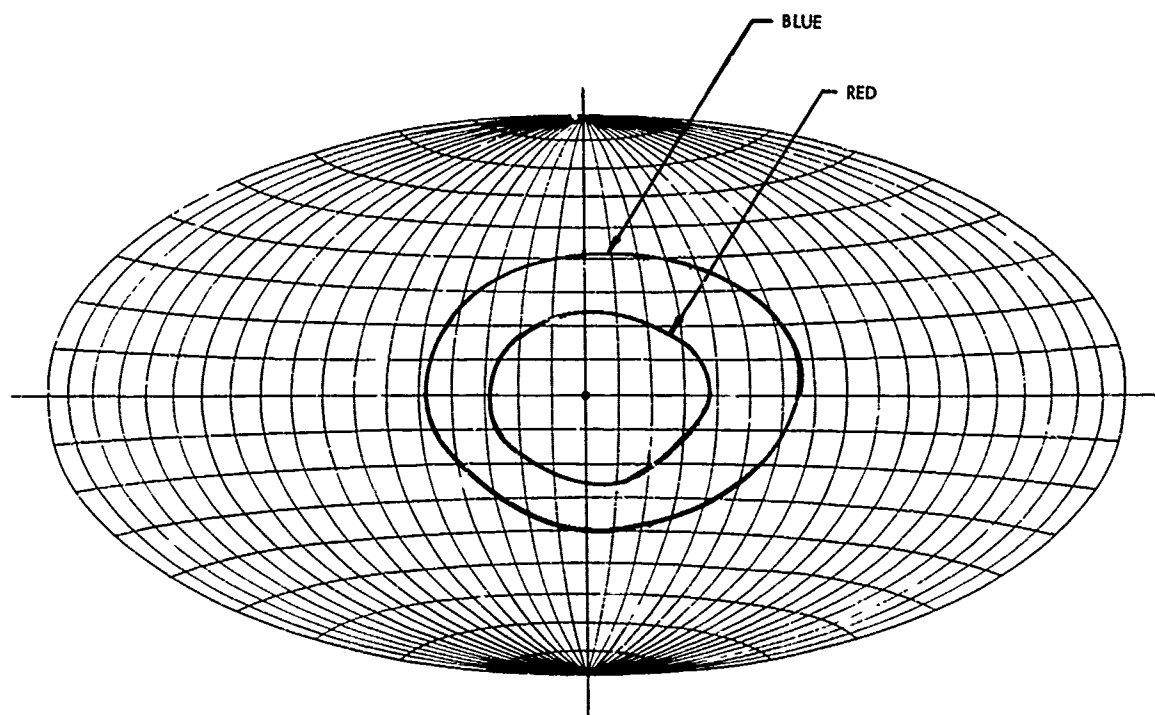
Figure 2.3   COLOUR ZONES FOR THE RIGHT EYE

Figure 2.4:   GENERAL VIEW OF TYPICAL HELMET/MASK COMBINATION

UNRESTRICTED VIEW

RESTRICTED VIEW
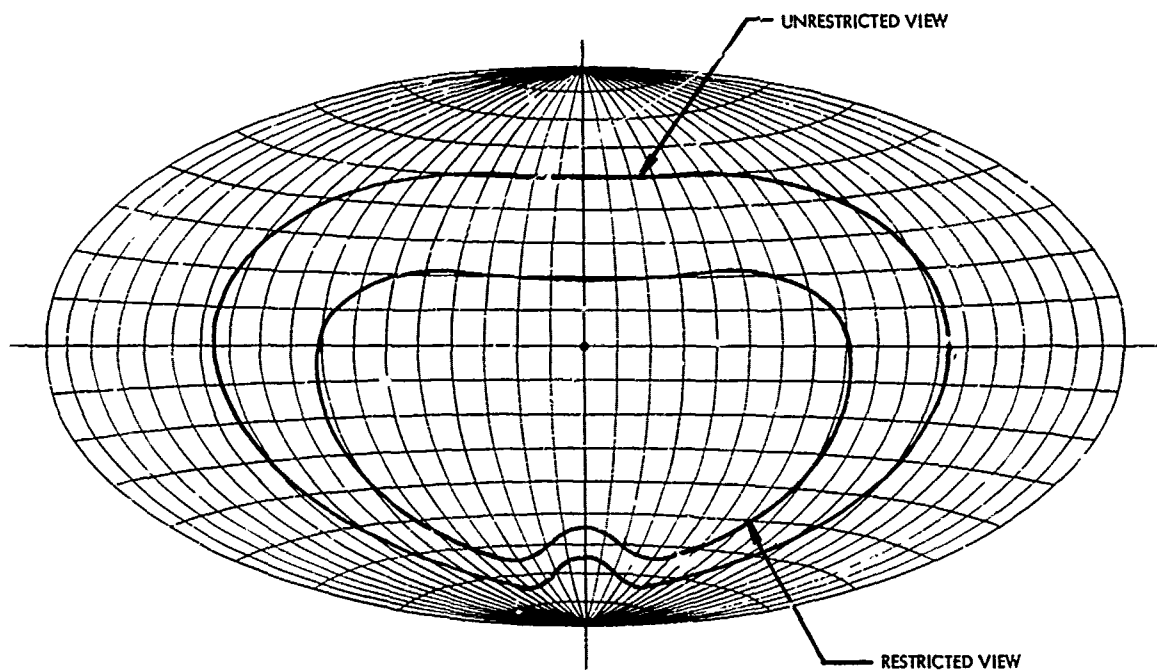
Figure 2.5 TYPICAL OBSCRULATION CAUSED BY HELMET/MASK
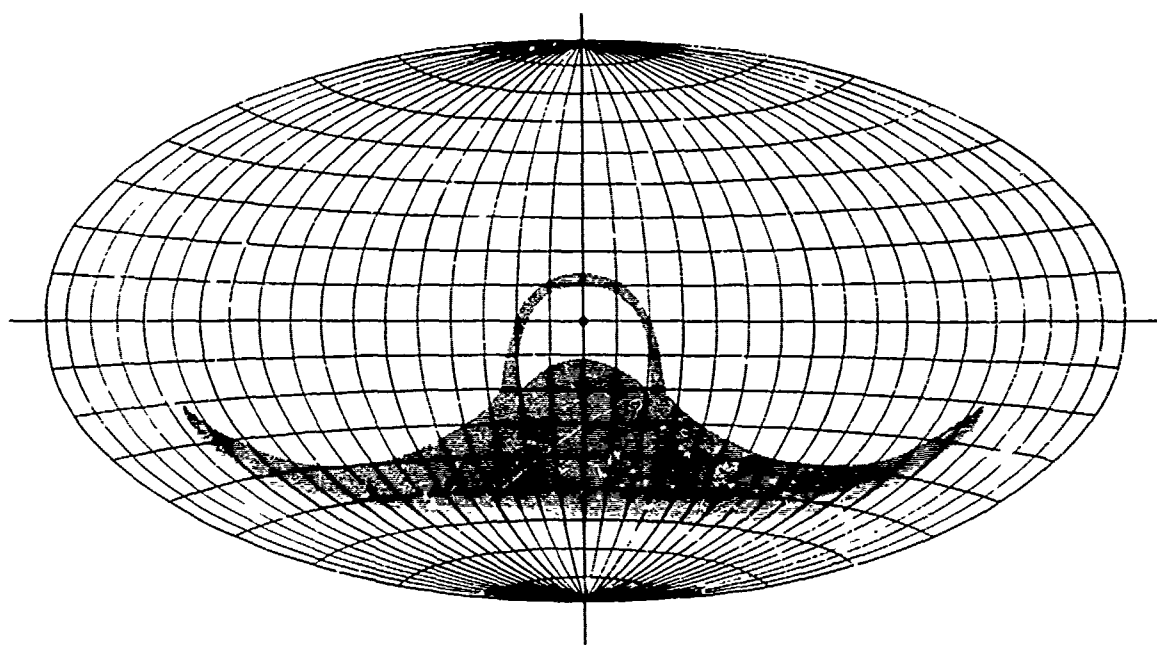
Figure 2.6 VIEW FROM MIL-STD-850B FIGHTER COCKPIT
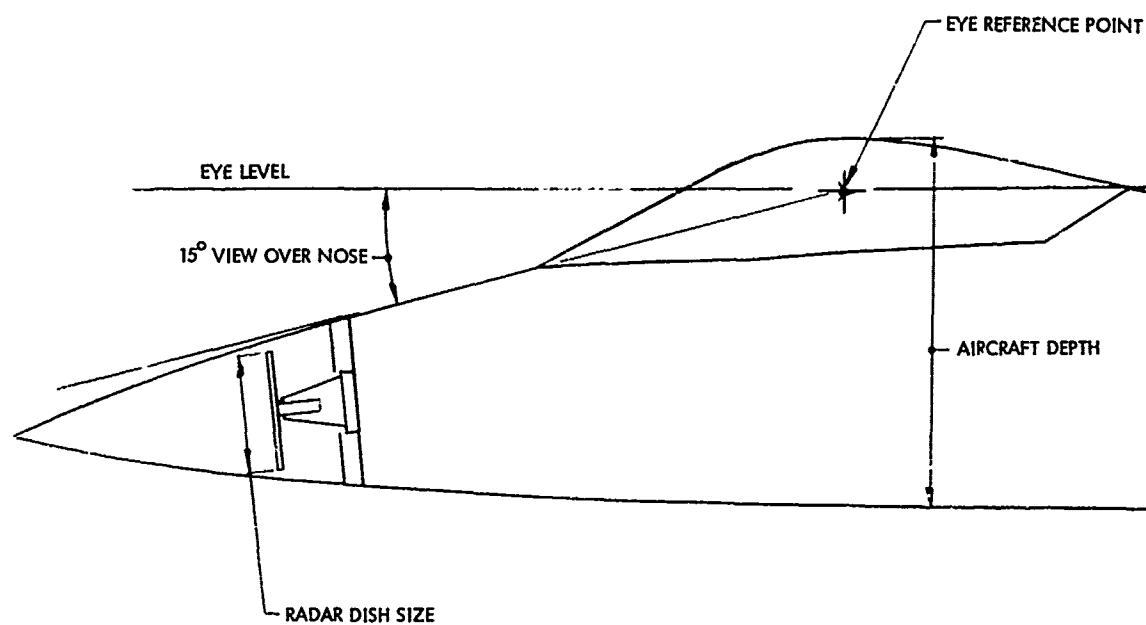
Figure 2.7   FACTORS INFLUENCING VIEW OVER THE NOSE
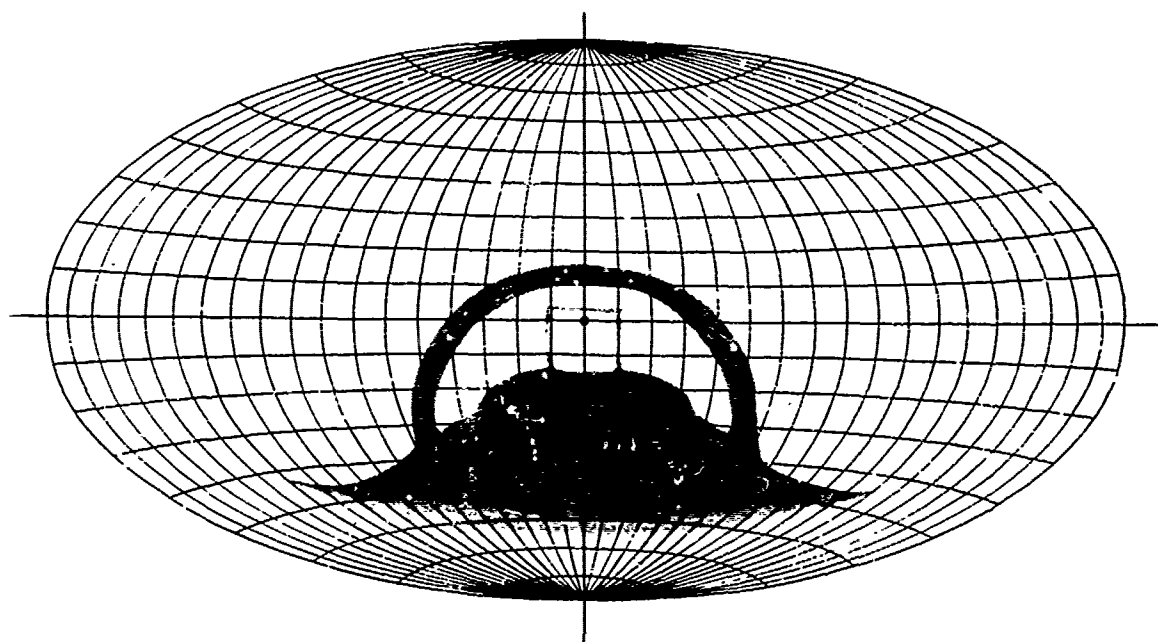
Figure 2.8   VIEW FROM ADVANCED COCKPIT
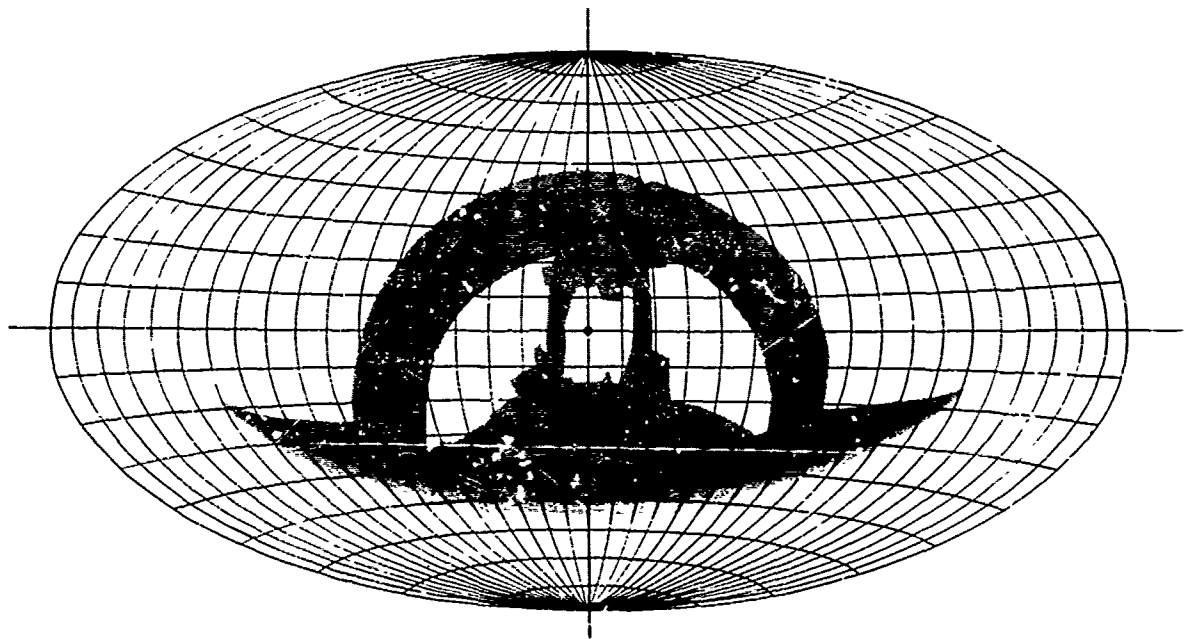
Figure 2.9   VIEW FROM BUCCANEER COCKPIT
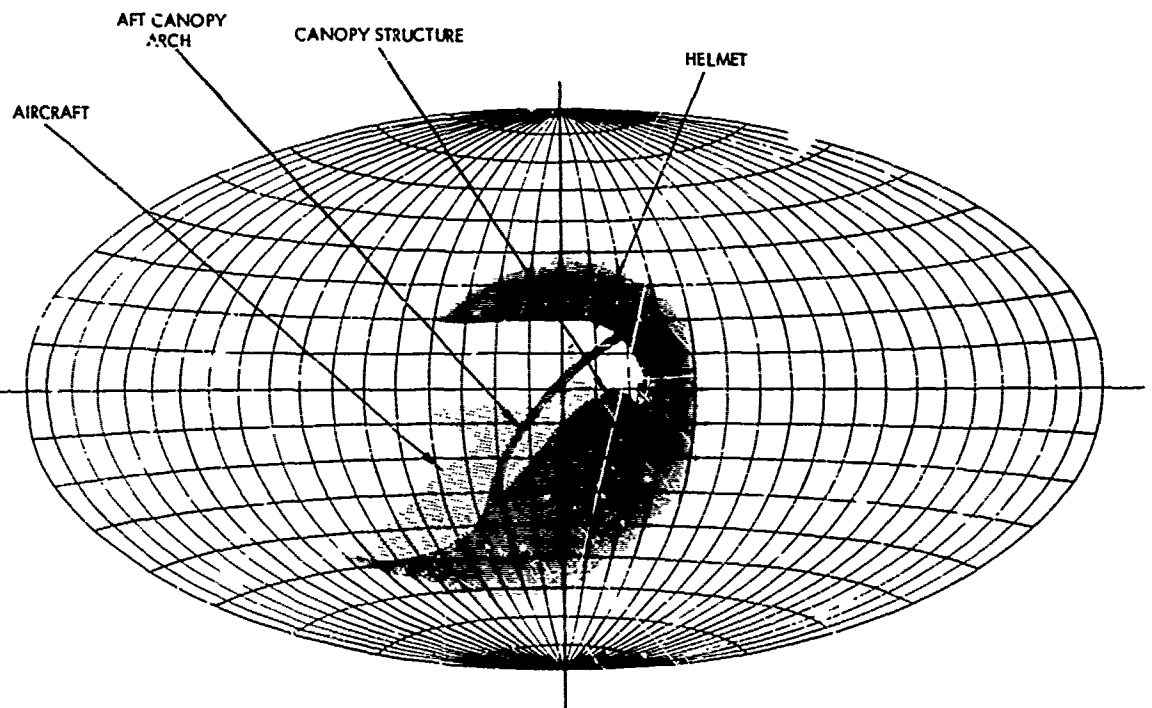
Figure 2.10   REARWARD VIEW FROM THE BROUGH ADVANCED COCKPIT

PROBABILITY OF TARGET
BEING UNMASKED
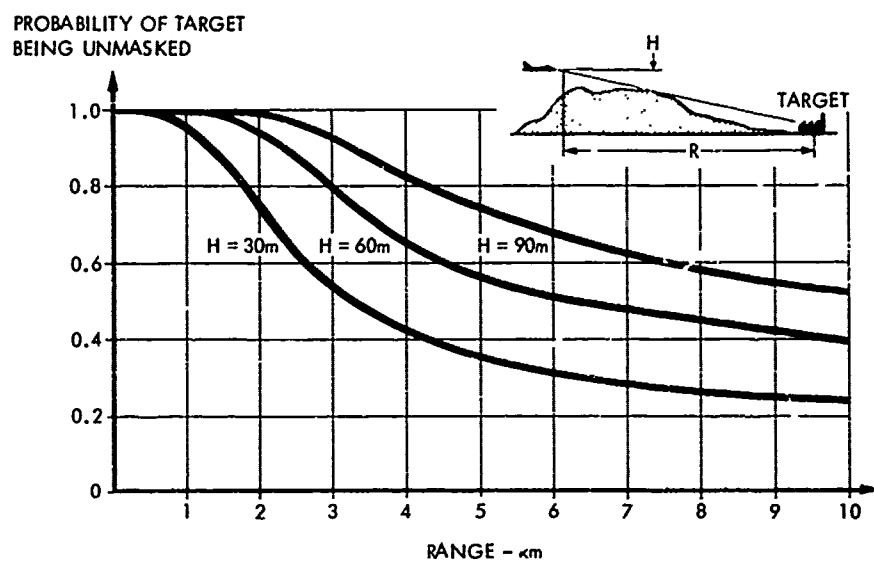
Figure 2.11   TERRAIN SCREENING PROBABILITY DISTRIBUTIONS
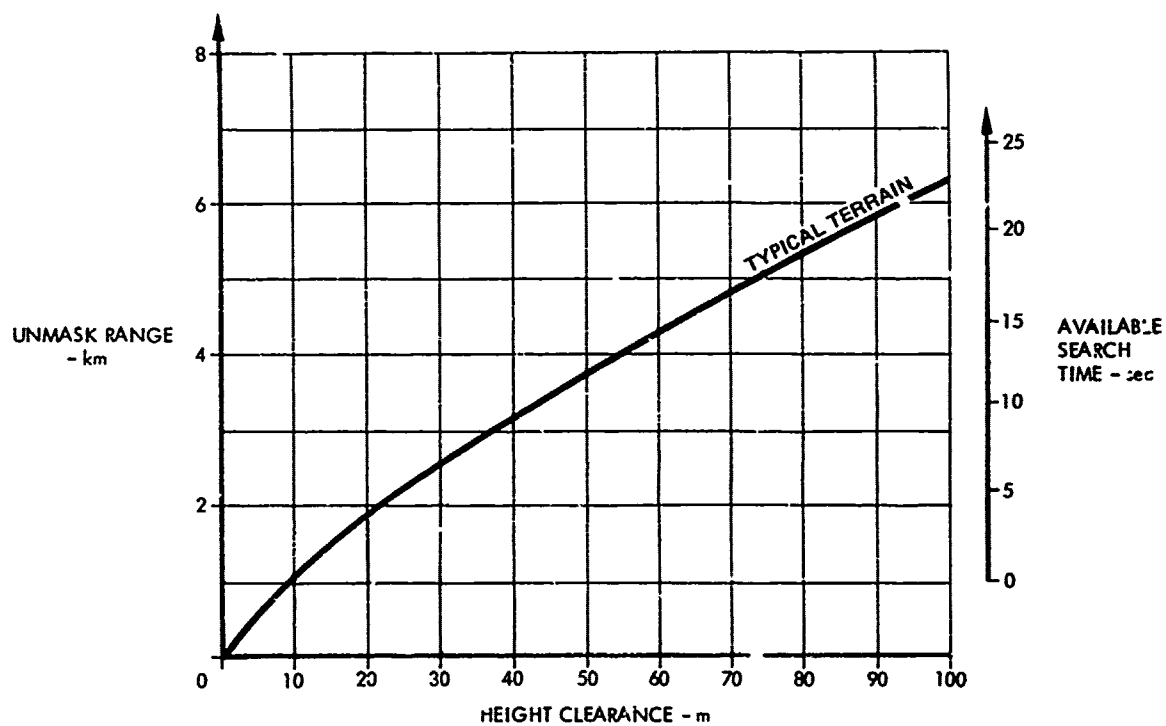
Figure 2.12   AVERAGE TARGET UNMASK RANGES

30m TERRAIN CLEARANCE
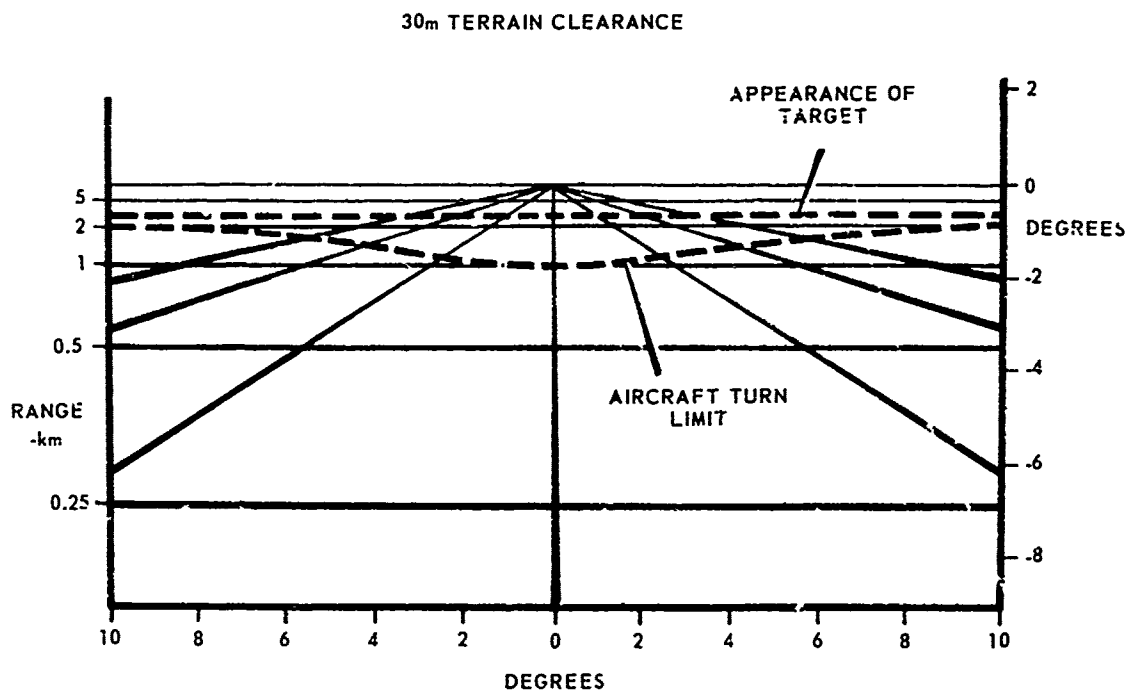
Figure 2.13 DISPLAY OF FLAT TERRAIN FROM 30 m

ATTACK ENVELOPES

	RETARDED BOMB, 1 SEC REACTION, 3 SEC TRACKING
——	RETARDED BOMB, 0 REACTION & TRACKING
	4 x 3m 50X AS APPEARS AT 0.5 & 1km RANGE
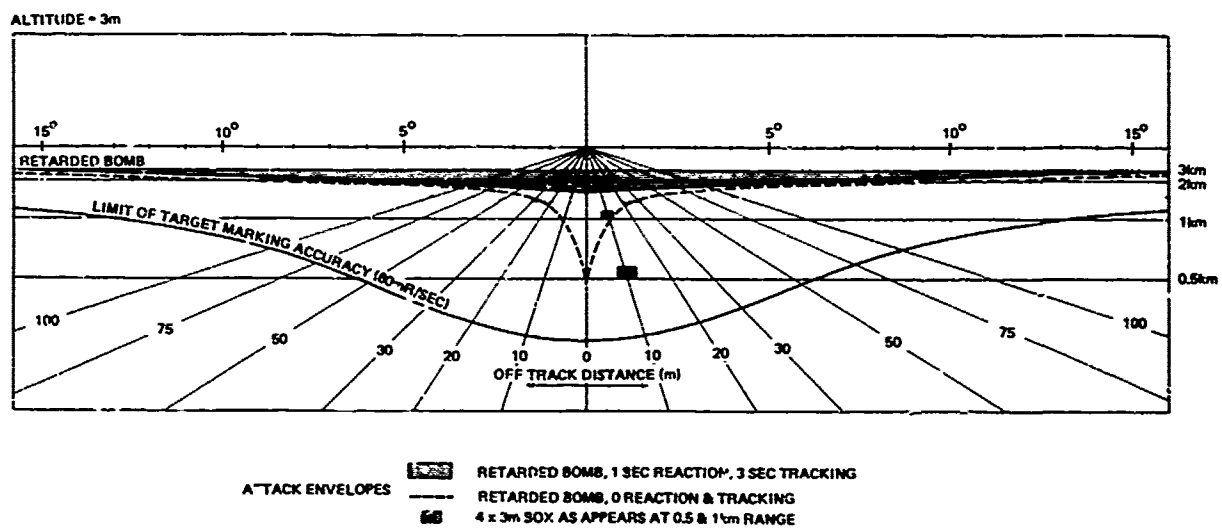
Figure 2.14 PILOT VIEW AND ATTACK ENVELOPE 30 m 450 KN
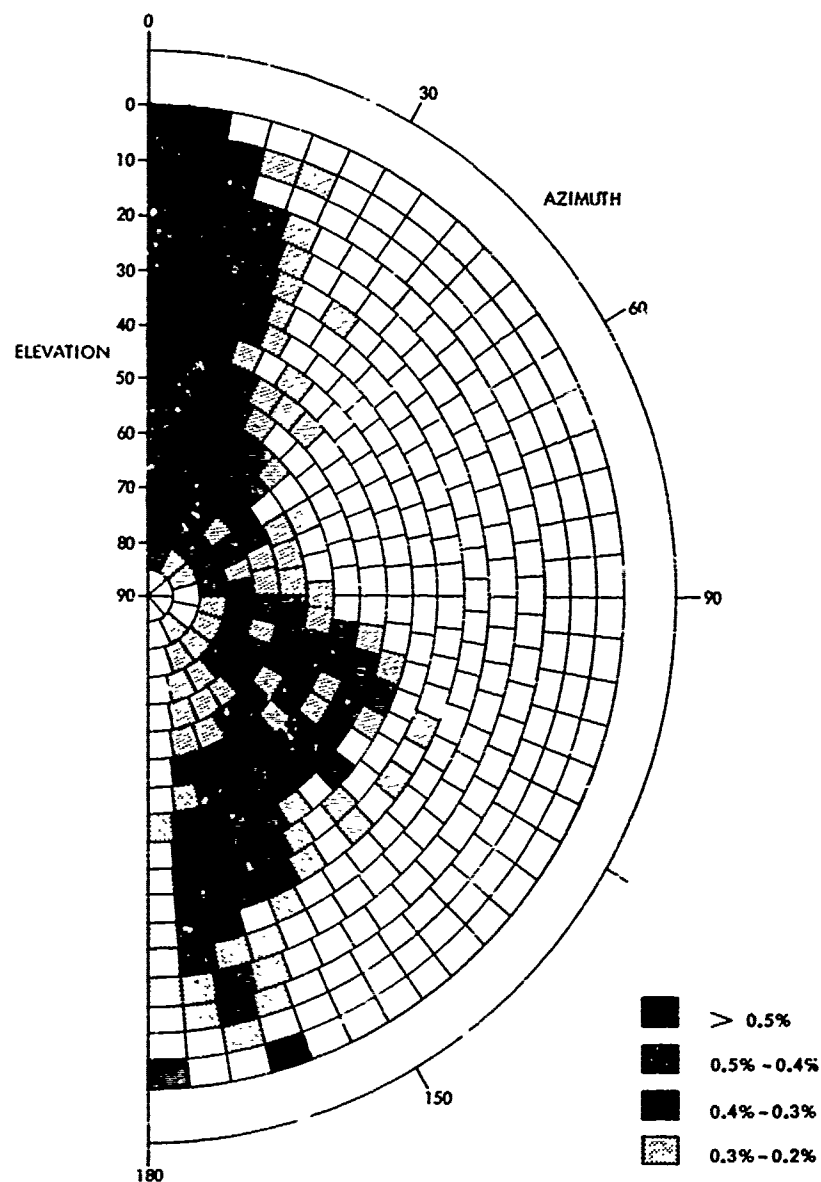
Figure 2.15 SIGHT LINE DISTRIBUTION

Legend:
- > 0.5%
- 0.5% – 0.4%
- 0.4% – 0.3%
- 0.3% – 0.2%
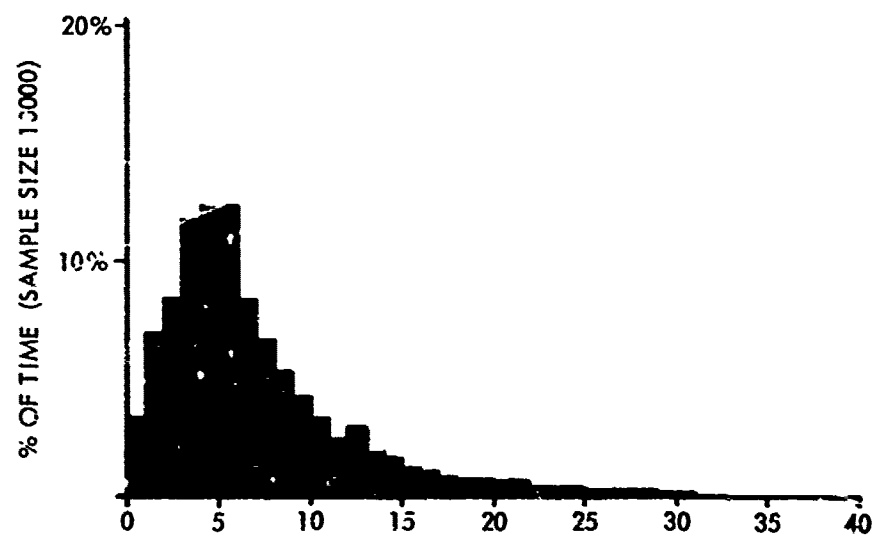
Figure 2.16 SIGHT-LINE SPIN DISTRIBUTION
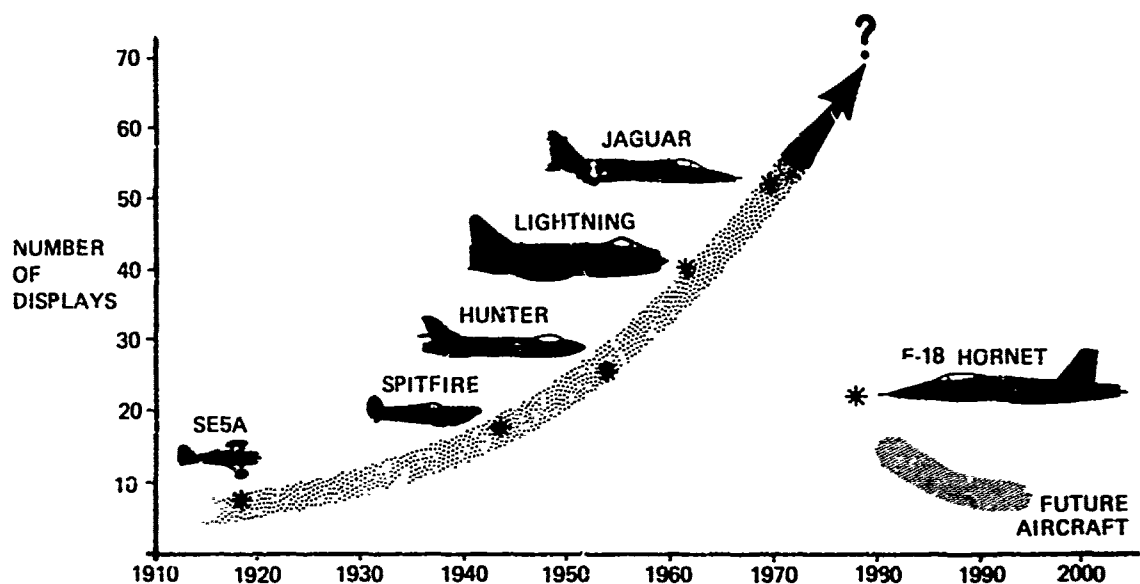
Figure 3.1 GROWTH OF COCKPIT DISPLAYS
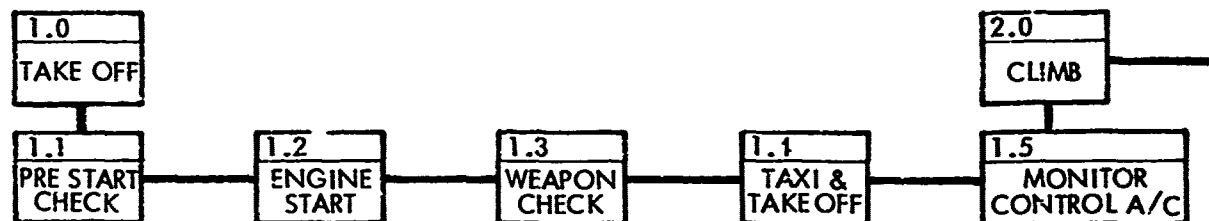
Function Number	Function Name	System Information Requirements	System Action Requirements	Machine Tasks	Man Tasks
1.1	Prestart check	Cockpit check			
		1. Integrity of system	1. Place all switches and controls to safe		1. Inspect
		2. Switches and controls 'safe' before power on	2. Adjust seat and rudder		2. All switches to safe
		3. Position seat and rudder	3. Connect umbilicals		3. Adjust seat to attain eye level
		4. Umbilicals	4. Connect straps		4. Connect umbilicals
		5. Straps	5. Ensure brake 'on' Measure, monitor, inform, select, test and warn	Measure, monitor inform, select, test and warn.	5. Fasten straps
		6. Brakes			6. Apply brakes 'on'
1.2	Power 'on'				

Figure 3.2 INFORMATION/TASK DEFINITION TECHNIQUE
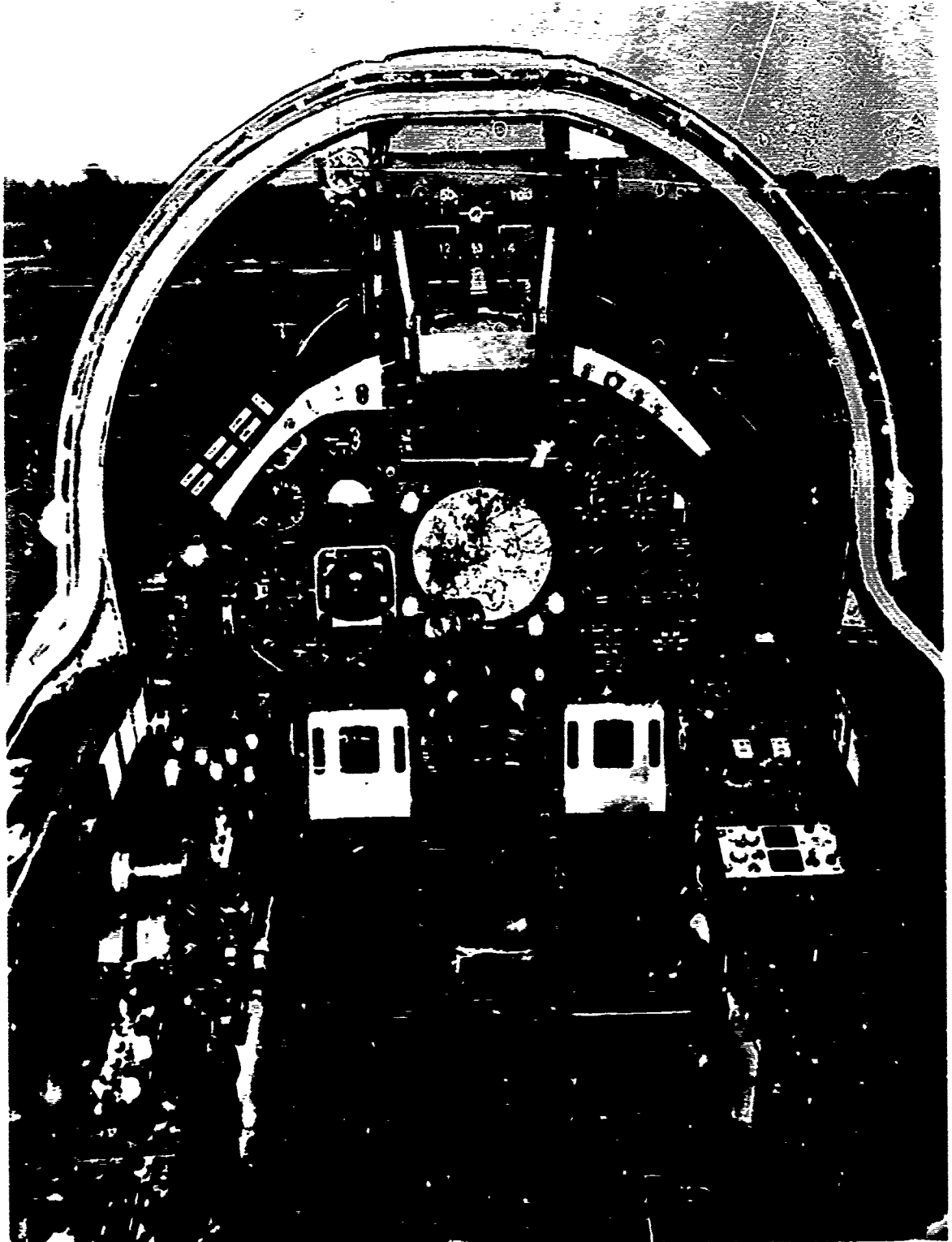
Figure 3.3 JAGUAR COCKPIT

HUD

HEAD LEVEL

MULTI PURPOSE 2

MULTI PURPOSE 1

INTER ACTIVE DISPLAY

N1BS
N4BS
W1BS
W4BS

Figure 3.4   CRUISE MODE
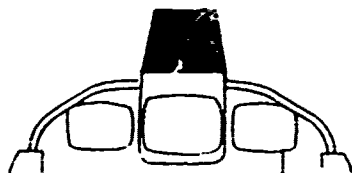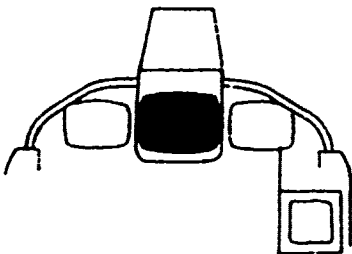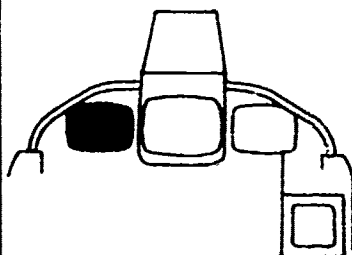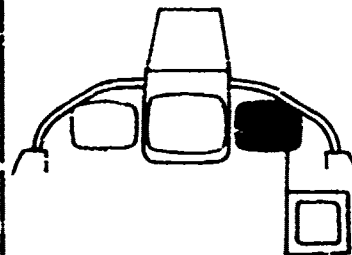
FLIGHT MODE	CRUISE
Head Up Display	A/C Symbol Pull Away Heading Pitch Precision Course Steering Vectors Radar On And Range To Target
Head Level Display	**MAP SHORT TERM NAV.** Map With Waypoints Known Threat Data Targets Present Position Distance To Go Time To Go Heading Speed (Knts) Height
Multi Purpose Display 1	**LONG TERM NAV.** Pre Planned Flight Plan (Grid North Up) Waypoint Update Points Targets Base Present Position Required Heading Actual Heading Nav. System Mode A/C Speed Height Time & Time Next Feature
Multi Purpose Display 2	**A/C SYSTEMS** A/C Speed Height Heading Present Position Fuel Remaining Comms Status Thrust Level Time GMT and E.T. Advisory Warnings

DISPLAY

Figure 3.5   DETAIL DESCRIPTION OF PRESENTED DATA IN CRUISE MODE

$$P = 1 - \frac{1}{(1 + 1/r \quad t/\bar{T})^{r}}$$
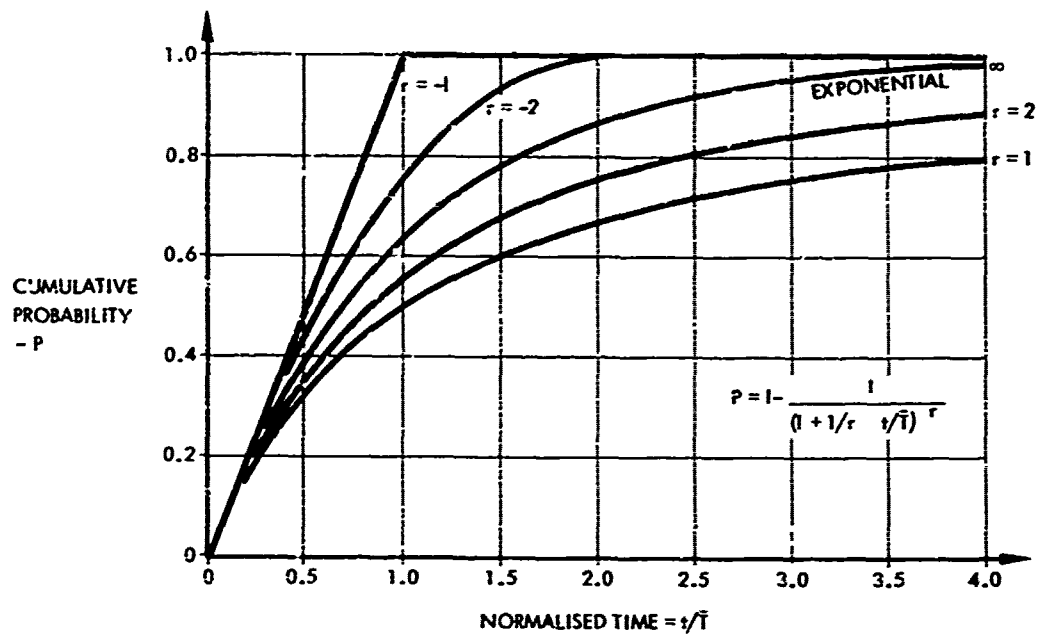
Figure 3.6   GENERALISED SEARCH DISTRIBUTION

DATA FROM REF. 3-1

SEARCH AREA STERADIANS

△	0.480
○	0.260
●	0.384
□	0.011

THEORETICAL CURVE

$$P = 1 - \frac{1}{1 + t/\bar{T}}$$
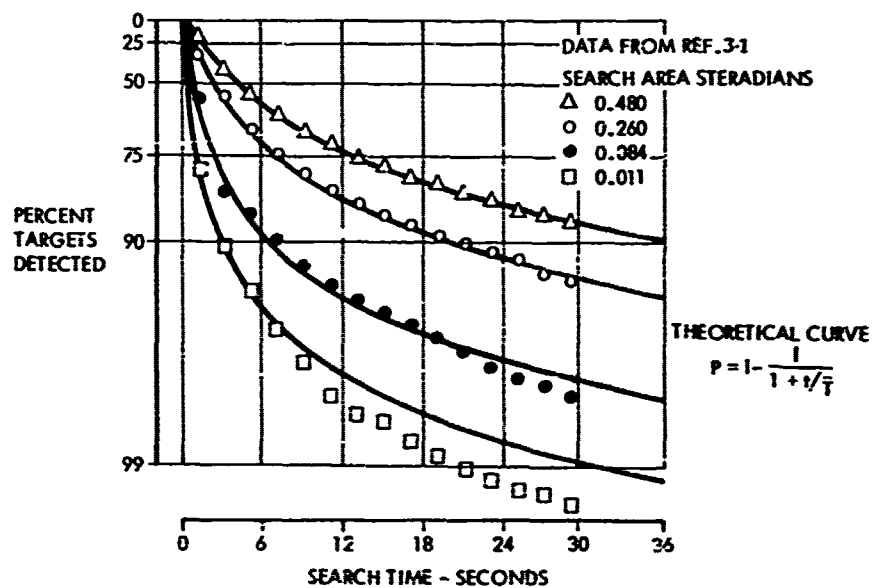
Figure 3.7   AN APPLICATION OF THE SEARCH EQUATION
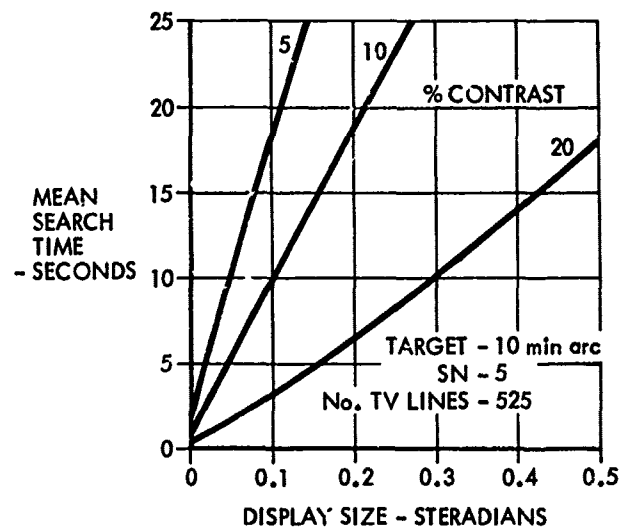
Figure 3.8   DISPLAY SEARCH
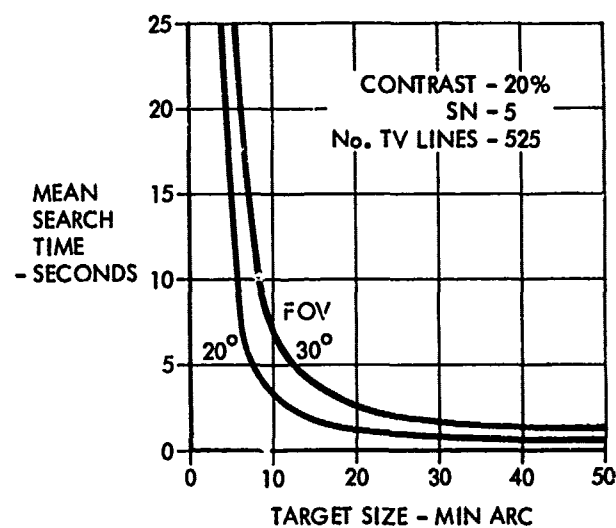
Figure 3.9   DISPLAY SEARCH
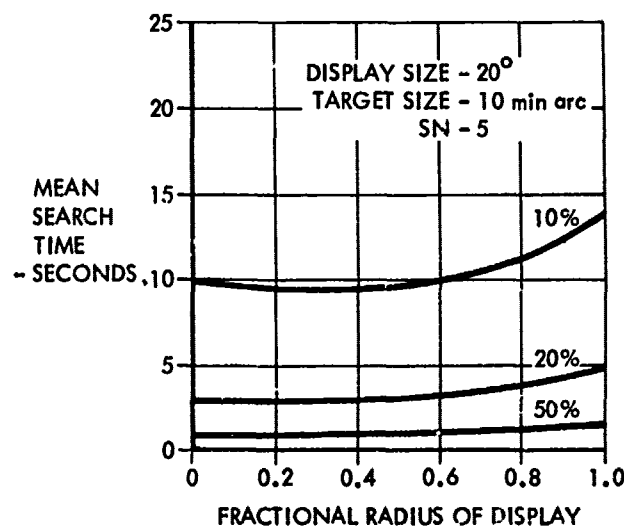
Figure 3.10   DISPLAY SEARCH
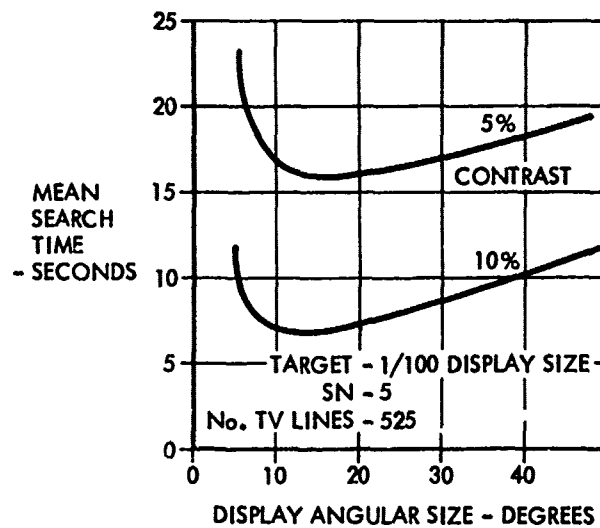
Figure 3.11 DISPLAY SEARCH
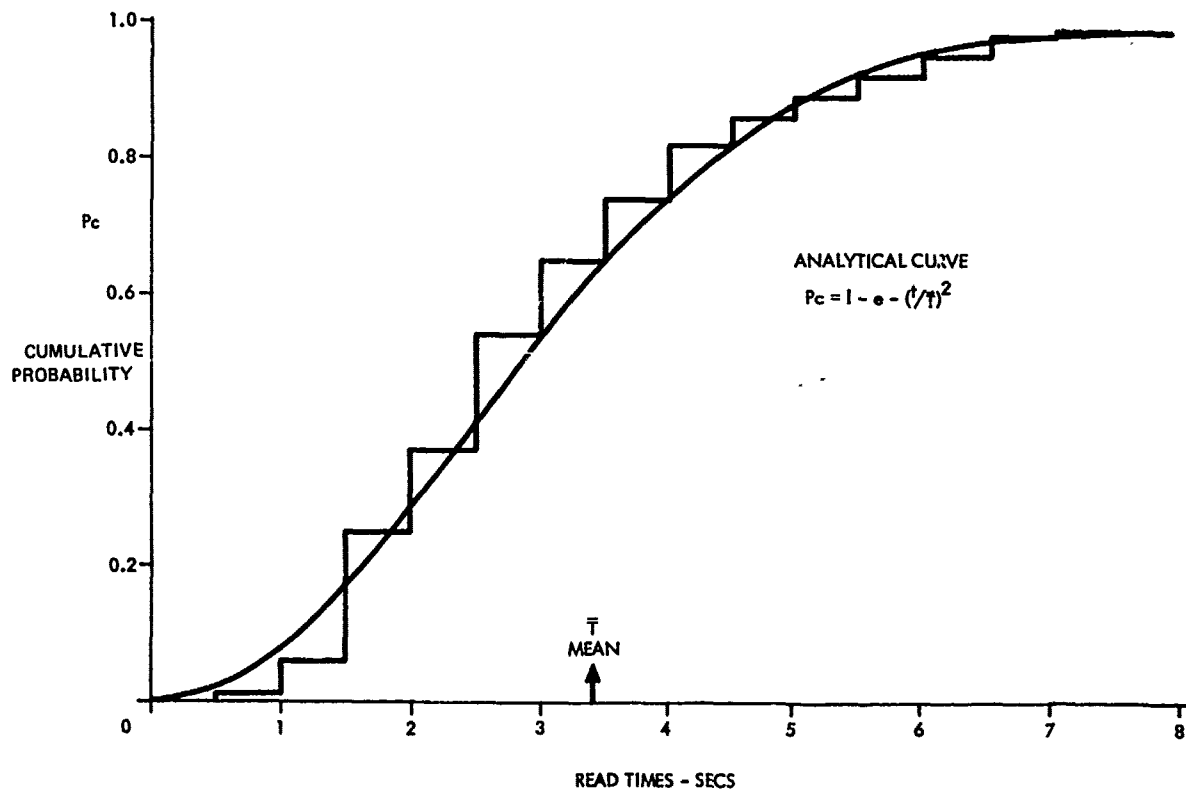
Figure 3.12 DISPLAY READ TIME DISTRIBUTION

TASK
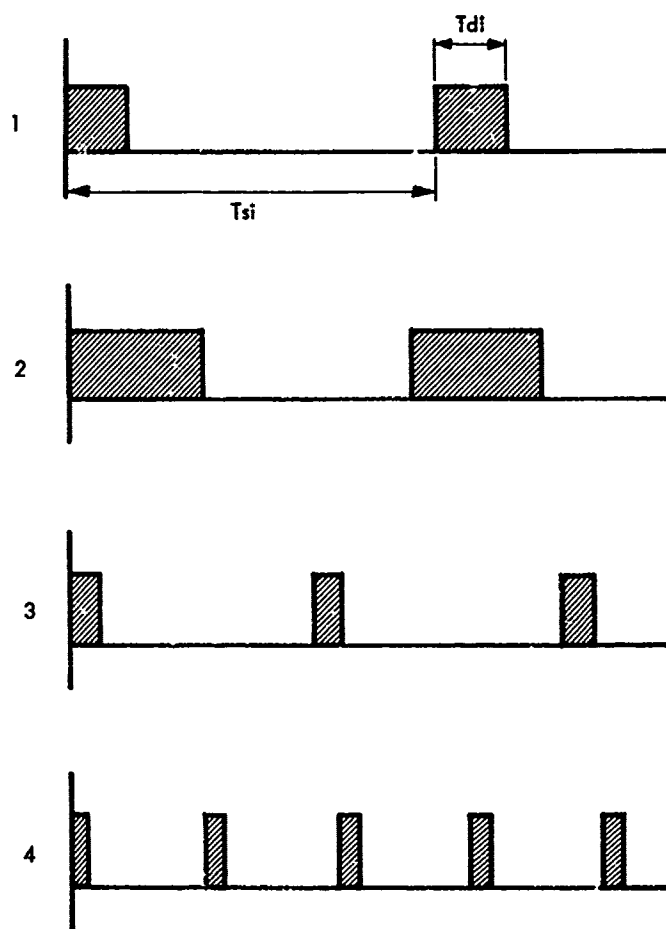
Tdi = DWELL TIME ON TASK i

Tsi = SAMPLING INTERVAL ON TASK i

$$\text{WORKLOAD INDEX} = \sum_{i=1}^{n} \frac{Tdi}{Tsi}$$

Figure 3.13 WORKLOAD ANALYSIS

LOOK ANGLE

-10° ELEVATION
0° AZIMUTH
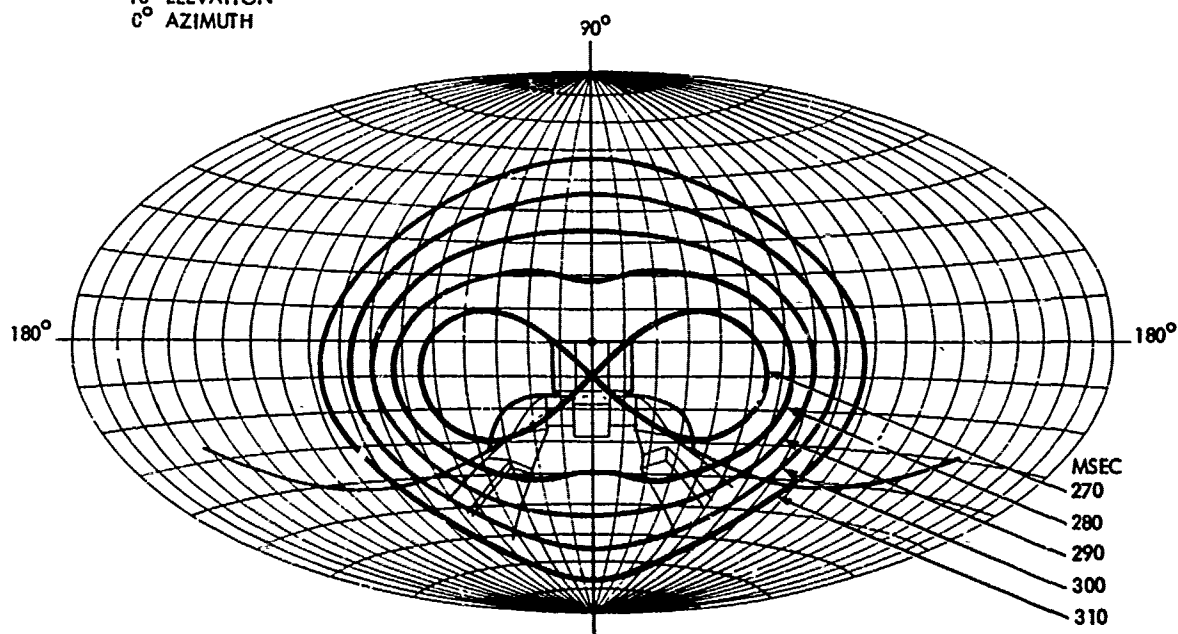
Figure 3.14 PILOT VIEW AND REACTION TIME

DISPLAY CONCEPTS FOR CONTROL CONFIGURED VEHICLES
by
Robert W. Klein
Guidance and Control Department
Grumman Aerospace Corporation
Bethpage, New York 11714
and
Professor Walter M. Hollister
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

SUMMARY

The unique flight modes of a Control Configured Vehicle (CCV) need to be taken into account in the design of displays for these craft. Several compensatory displays are suggested and evaluated using a fixed-base, F-16 CCV simulation. The displays were found to enhance the improved tracking performance available when CCV modes are used in comparison to conventional flight.

INTRODUCTION

The United States Air Force has utilized several test beds for the design and evaluation of Control Configured Vehicle (CCV) concepts (i.e., B-52, F-4, F-8, F-16). The F-16 CCV is chosen as an example here to utilize recent F-16 CCV flight test and evaluation results and available aircraft dynamics data. CCV and Display research conducted in the past 15 years has been done independently. There has been virtually no research conducted combining Advanced Display Concepts with the CCV aircraft. In this paper progress on Control Configured Vehicles and Advanced Displays is analyzed, and candidate displays for CCV aircraft are developed. It is important to understand the display design as part of a total closed loop system including the pilot, pilot's controls and aircraft dynamics. Since the F-16 CCV offers decoupled aircraft dynamics, isometric controls and fast sensors, the opportunity exists for significant performance improvement and reduced pilot workload with an advanced, task-oriented CCV display system.

The F-16 Control Configured Vehicle

As part of its continuing progress in the area of Fly-By-Wire control systems, mission-tailored control modes, advanced displays and decoupled flight path control, the Air Force Flight Dynamics Laboratory contracted with General Dynamics in 1973 for an 87 flight, 125 hour test program of the F-16 CCV (Ref. 9). Flight testing of the F-16 CCV marked the first exploitation of decoupled six-degree-of-freedom flight path control. Completed in June 1977, test pilots evaluated the CCV control modes in air-to-air and air-to-ground missions. The test program validated the new CCV control concepts and demonstrated significant potential to enhance the overall mission effectiveness of fighter aircraft.

Modifications to the F-16 include vertical canards added to the forward fuselage with structural beefup, isolation of the right and left fuel tanks allowing manual CG control for relaxed static stability performance improvements, flight control system modification for implementation of CCV modes, and utilization of wing flaperons for additional functions. In the cockpit, the trim button on the sidearm controller was replaced with a two-axis force controller to activate and control the CCV modes. A CCV control panel was added in the forward cockpit for selection of the various longitudinal and directional CCV modes controlled by the sidearm-mounted, 2-axis force controller and former "rudder" pedals. In addition, canard, rudder, wing flaperon and horizontal tail angles along with sideslip angle and lateral acceleration states were displayed on the forward display system.

Once the flight control system feedback loops were properly modified and compensated, 6 new "decoupled" flight control modes were possible for CCV button and pedal inputs. These new modes were horizontal and vertical direct force, fuselage pointing, and translation. All the longitudinal modes are vertically activated by the thumb controller; the directional modes are either activated by horizontal thumb controller movement or by the rudder pedals (this selection may be made on the CCV control panel). The design is such that the pilot does not have to move his hands or feet from the conventional controls to utilize the CCV modes; they do not disturb normal aircraft operation and augment the fighter capability.

An additional maneuver enhancement mode (activated by an on/off button) enhances pull-ups and helps to alleviate gust disturbances (reducing RMS aircraft response to gusts 20% to 30% (Ref. 2). The F-16 CCV mode operations were recorded during flight test by quantitative tracking recordings and pilot Cooper-Harper ratings and qualitative pilot comments. The evaluations provide insight in choosing the most viable CCV modes and in designing a proper display to augment the pilot/CCV aircraft performance.

Heads Up Displays

A decision to choose Heads Up Display (HUD) to augment the CCV aircraft follows from an analysis of the CCV aircraft/mode controller/pilot interface. The flight regimes where CCV modes will improve fighter performance are air-to-air combat, air-to-ground weapons

delivery and landing in variable weather conditions. In all these missions the pilot's attention will be focussed outside the aircraft, at another aircraft, a ground target, or the runway. The Heads Up Display allows the pilot to keep his attention oriented outside, with his eyes focussed at infinity. The measured and displayed information are in one-to-one correspondence with the outside world. While CCV modes add direct force, pointing, and translation modes, the pilot may no longer determine velocity vector direction by aircraft attitude. For this reason test pilots recommended an HUD presentation of the velocity vector and pointing direction (Ref. 1).

Figure 1 illustrates how a Heads Up Display system operates. By projecting flight information through a lens on a half silvered mirror oriented inside the canopy, the pilot may simultaneously view the outside world and flight data focussed at infinity. Delays are eliminated in refocussing his eyes from infinity to the instruments and back to infinity again. The dangerous transition from flying heads down on instruments to heads up is no longer necessary. The pilot also feels more confidence in his instruments since the flight data is in a simultaneous one-to-one correspondence with the outside world. The time delay in scanning from one instrument to another is significantly reduced since most of the relevant flight information is integrated on the HUD display.
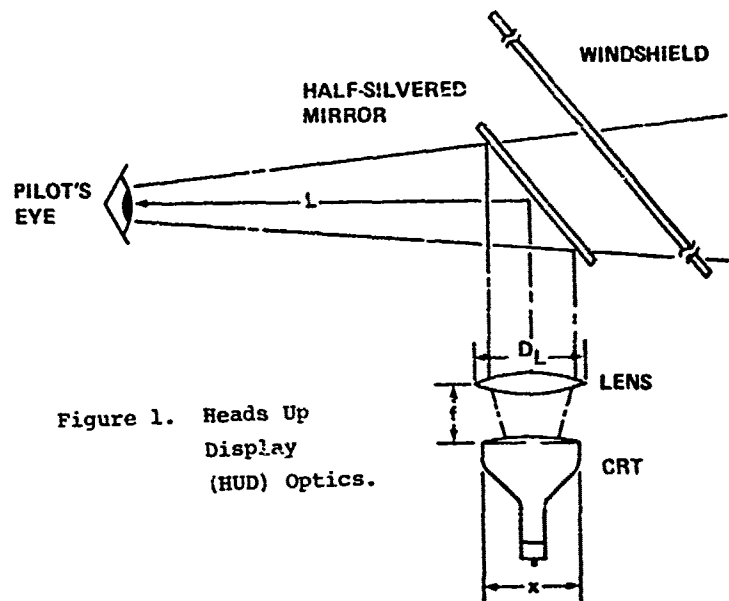
Figure 1. Heads Up Display (HUD) Optics.

Figures 2 and 3 show how the flight information and outside scene appears through the HUD. The primary information a HUD should display is the flight vector, the horizon, and the intended track or target superimposed over the actual view. Other information which can be displayed is an aircraft attitude symbol, reference angle-of-attack, limit angle-of-attack (stall) and potential path (the path of the aircraft in accelerated flight). The potential path is used for thrust management: when the symbol is above the velocity vector excess thrust exists and when the symbols coincide, the velocity is stabilized. Similarly, when the velocity vector is above the horizon the aircraft is climbing and when below the horizon it is losing altitude. When in one-to-one correspondence angularly with the outside view, flight data is easily visualized, the aircraft is more easily controlled with a reduction in pilot workload.

If the velocity vector, horizon, and aircraft body axis are displayed on the HUD as in Figure 4, the following angles are readily apparent. (see next page)

In general, a pilot can monitor seven to eight data items without difficulty, according to research carried out by the Royal Aircraft Establishment, Farnborough, England (Ref. 19). Thus the display should be designed to show only those instrument readings necessary for a given mode of flight. The highest priority data should be close to the nominal field of view to reduce scan lag. Information should be displayed in the appropriate analog (compensatory) or digital (numerical) form to minimize pilot workload. Large eye movements should be minimized, and the display axes should physically correspond with the outside world (ex. altitude along the vertical axis, heading angle along the horizontal axis), in "natural display directions" (as viewed from the aircraft outward). The nearness of the display to the nominal point of view and its priority should follow a Gaussian distribution (the most frequently scanned displays closest). Displaying information in the appropriate analog ("tape") or digital form should minimize both interpretation and compensatory workload. In determining the HUD dimensions, the scale must be fine enough to perceive several mils of pipper error for adequate tracking performance. At the same time, the field of view must be wide enough so that velocity, heading and altitude may be peripherally displayed without interfering with target acquisition. Since angular
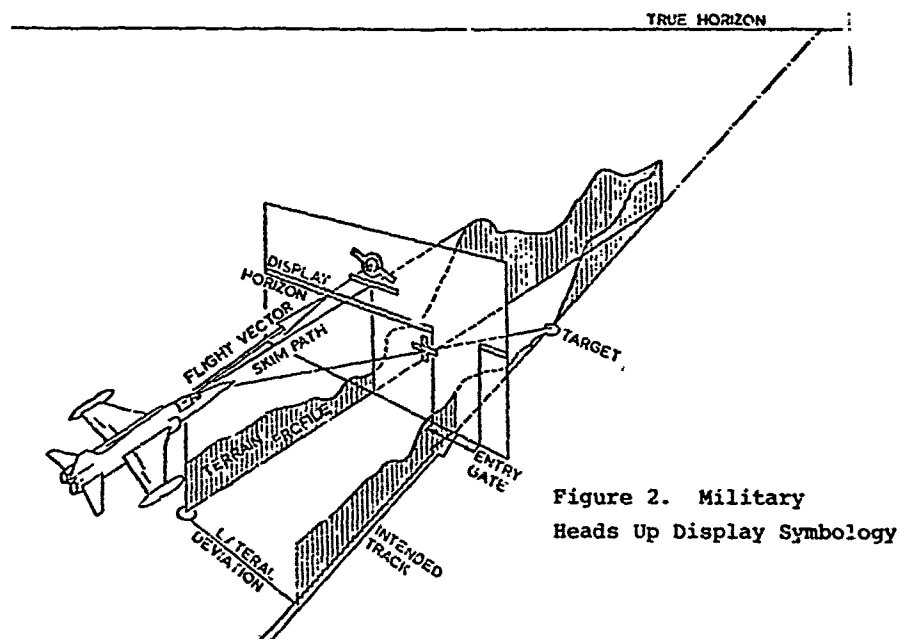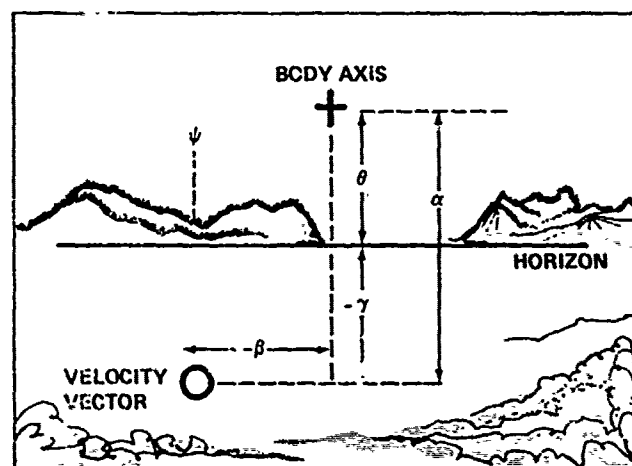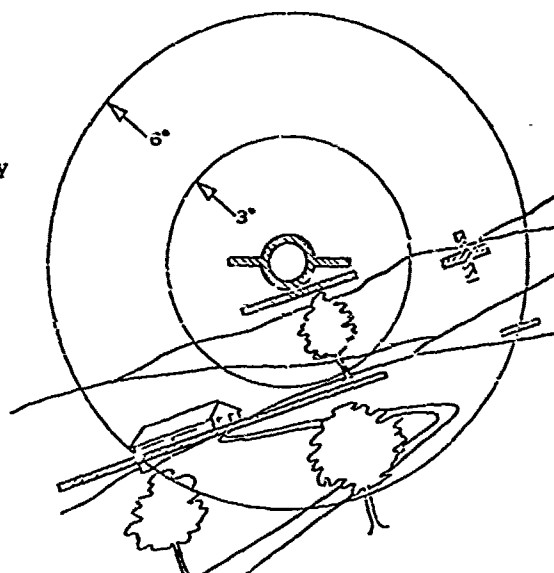
Figure 2. Military
Heads Up Display Symbology

Figure 3. Typical
View through Military
HUD; eyeheight 60m,
140m below target at
4000m distance, 20°
right bank.

HEADING: ψ

SIDESLIP: β

ANGLE OF ATTACK: α

FLIGHT PATH ANGLE: γ

PITCH ANGLE: θ

Figure 4. Flight information (such as velocity V, vertical velocity h) can be
visually deduced from the overlay of the horizon, body axis and velocity vector
symbols on the real world.

relationships are preserved between the HUD display and the real world, and the HUD is nominally located approximately 19" from the pilot's eyes, a 10" HUD screen will yield a 2 $\tan^{-1}$ (5/19) or 30° field of view. This appears appropriate for the ± 5° pointing authority (a 10° diameter circle in a 30° by 30° field) and the angle of attack variation from high to low speed operation.

Display Design for the CCV Aircraft

In designing an appropriate advanced display to fully augment CCV performance, one should consider the display as part of a closed loop system, Figure 5, where the double line denotes a matrix of states and control actions. In a conventional system, the pilot
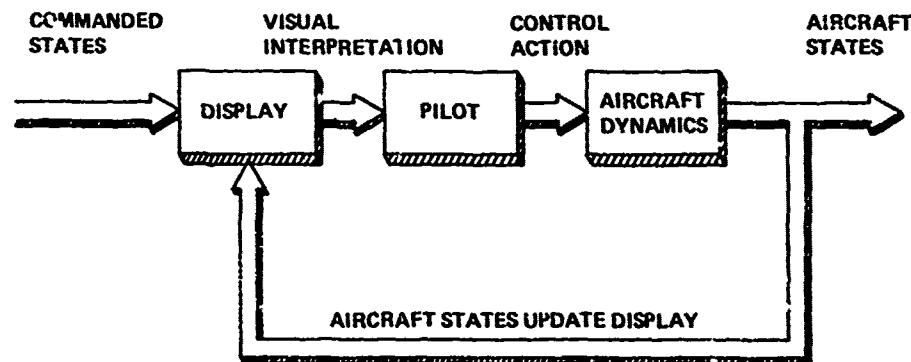
Figure 5. The Display System as part of the Total Pilot/Aircraft System.

must utilize several controls in a closed loop fashion to bring about a commanded state. Here the pilot adjusts his internal transfer function to effectively decouple the system. In general, the human controller is not particularly efficient at decoupling multiple degree-of-freedom, coupled systems; such systems increase the workload of the pilot. For instance, in initiating a heading change, the pilot must utilize the aileron, rudder and elevator to initiate the bank, to bank, and return to wings level flight when the desired heading change is achieved. The aircraft is strongly coupled and the pilot must apply "lead" or anticipate when to complete the maneuver. The decoupling and lead the pilot must apply corresponds to an increase in concentration during the maneuver and thus an increase in pilot workload.

Herein lies the advantage of the CCV aircraft. One control may be utilized to command a change in one state; with properly designed decoupling of the CCV mode dynamics and controller implementation, the task is easily conducted by the pilot. In the above example, in the CCV direct side force mode, the rate of change of flight path angle is directly proportional to the lateral thumb force on the "Coolie Hat" thumb controller. The CCV aircraft response is decoupled, the heading change is easily conducted (without internal decoupling or lead generation by the pilot), resulting in a reduction of pilot workload. By being decoupled and proportional to one controller input, the longitudinal and lateral direct force, pointing, and translation modes offer strategic new aircraft control capabilities.

There are already features of conventional displays which augment CCV performance. Since the modes are decoupled, pure vertical or horizontal slew rates are obtained for vertical or horizontal forces on the thumb controller (diagonal forces yield a vector sum of horizontal and vertical rates). Thus the conventional system of crosshairs serves as a great aid in compensatory tracking or nulling the diagonal offset of a target. In tracking with the thumb controller one aims for the intersection of the crosshair axis (Figure 6). If one axis is met, the human controller knows to translate purely along that axis.
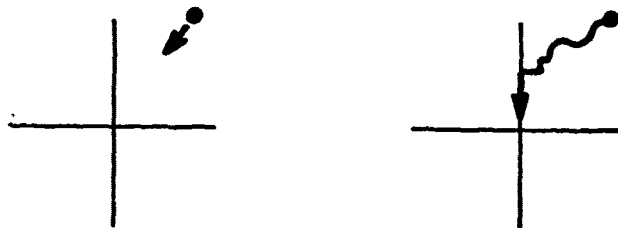

Figure 6. Nulling Offsets Utilizing Aircraft Crosshair System.

The responses to horizontal and vertical inputs are parallel to the axes. In this way the CCV inner display design (inner portion of HUD) has been reduced to human compensatory engineering analysis.

In nulling the pointing error the display should improve CCV performance if it displays aircraft slew rate magnitude and direction. These are sensed on the thumb controller (slew rate is proportional to force on thumb controller), but the authors believe that force magnitude and angle is not sensed accurately enough by the thumb. A proper display of CCV slew rates and direction of slew would augment CCV performance in air-to-air and air-to-ground tracking. One possibility is a vector display (Figure 7) which shows the
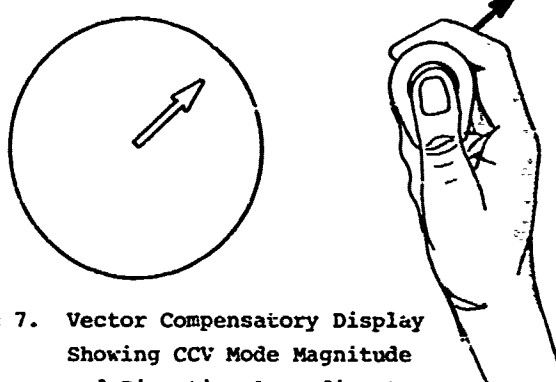
Figure 7. Vector Compensatory Display
Showing CCV Mode Magnitude
and Direction According to
"Coolie Hat" Activation.

magnitude and direction of the slew rate. The human controller, visualizing the actual slew rate magnitude and direction, can change the force and direction exerted on the thumb controller to null the pointing error. The overall CCV tracking capability should improve since the display applies an additional more accurate feedback to the pilot than the force feedback from the thumb controller.

If there is concern that the arrow will interfere with target acqui-ition, another display could be a line showing the angular direction of the thumb force exerted on the 'Coolie hat" (Figure 8). Angular data, rather than magnitude data, is presented since the
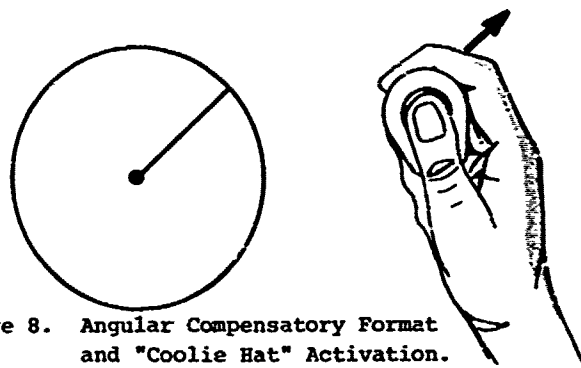
Figure 8. Angular Compensatory Format
and "Coolie Hat" Activation.

thumb probably senses force level better than force direction, and thus it is force direction data that is incorporated in the display.

Another feature which should be incorporated is an authority circle. With equal pointing capability in pitch and yaw, the circle illustrates the region in which CCV pointing modes may be utilized. No guesswork is necessary: once the pilot acquires the target within the authority circle, he may utilize the quick, decoupled CCV modes for precise aiming. Thus for the pointing mode, there are two candidate compensatory formats. Figures 9a and 9b show the authority circle (limit of CCV pointing authority) and their respective compensatory formats. In Figure 9a the magnitude and direction of the pointing slew rate is indicated by the length and direction of the displayed vector (the maximum slew rate is indicated when the vector tip reaches the authority circle). In Figure 9b the location of the line on the authority circle indicates the slew rate direction. Both of these candidate compensatory formats aid in the utilization of the pointing CCV mode.

Similar magnitude and direction information could be displayed for the direct force and translation modes (e.g. for acceleration, vector length and direction indicates magnitude and direction of acceleration, maximum vector length inside authority circle corresponds to maximum CCV acceleration). The nominal velocity vector would serve as the vector origin with a deadband for small force inputs. Thus either Figure 9a or 9b could be used for compensatory tasks involving the direct force, pointing or translational CCV mode, depending on which mode was presently in operation.

The next step is the display of numerical flight data. This includes airspeed, rate-of-climb, heading, and altitude. Airspeed will be displayed along the left border, heading

along the top, and rate-of-climb and altitude along the right hand side. An artificial horizon will be displayed along with pitch angle demarcations at $\pm 5°$ and $\pm 10°$. Numerical data will be towards the outside of the display (to avoid clutter with the target and
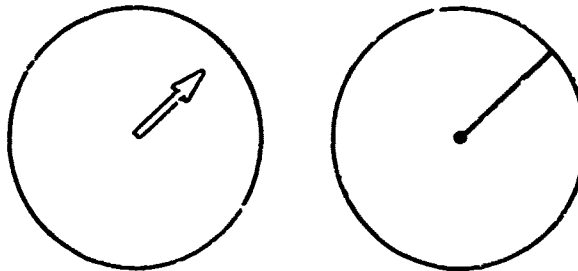
Figures 9a,b   Vector (a) and Angular (b) Compensatory Formats
with Authority Circle.

symbols). Desired and actual readings of the flight data will be displayed with triangles in analog form. The analog "tape" form has been chosen since flying is a compensatory task and pilot workload is lower nulling analog "tape" errors rather than reading a digital format, interpreting the data and making an appropriate control action (rate information is lacking in the digital display format).

Based on the analysis of CCV operation and advanced displays, the candidate Heads Up Displays shown in Figures 10 and 11 are proposed.
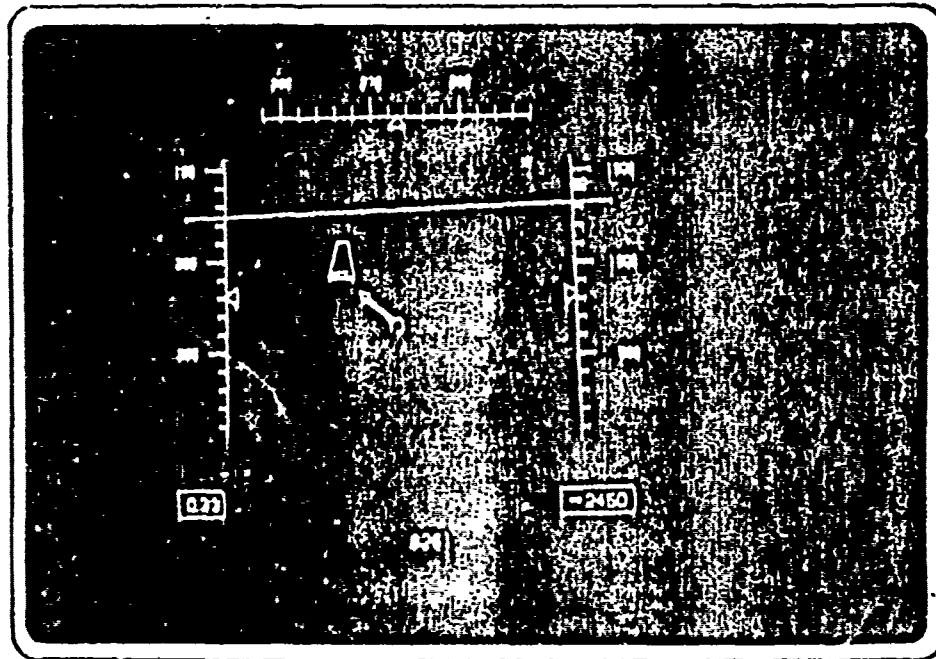
Figure 10.   Candidate Heads Up Display Proposed with Compensatory Display (Arrow)

Development of an F-16 CCV Simulator

In order to evaluate these concepts an existing 707 simulator was converted to an F-16 CCV simulator with an advanced Heads Up Display (Ref. 36). The 707 simulator had been developed over several years' effort in work by Connelly on Airborne Traffic Situation Displays (Ref. 37). Extensive modifications had to be made to the assembly language programs to accommodate the F-16 aircraft dynamics. A Heads Up Display was programmed with moving tape scales for airspeed, heading, and altitude. Rate of climb/sink and Mach number values were displayed in a digital format, and the designed compensatory displays were also included on the HUD. A numbered runway and horizon line was added to represent the external scene, including rigorous transformations incorporating the aircraft positional perspective and attitude. The interior of the cockpit was modified to represent a
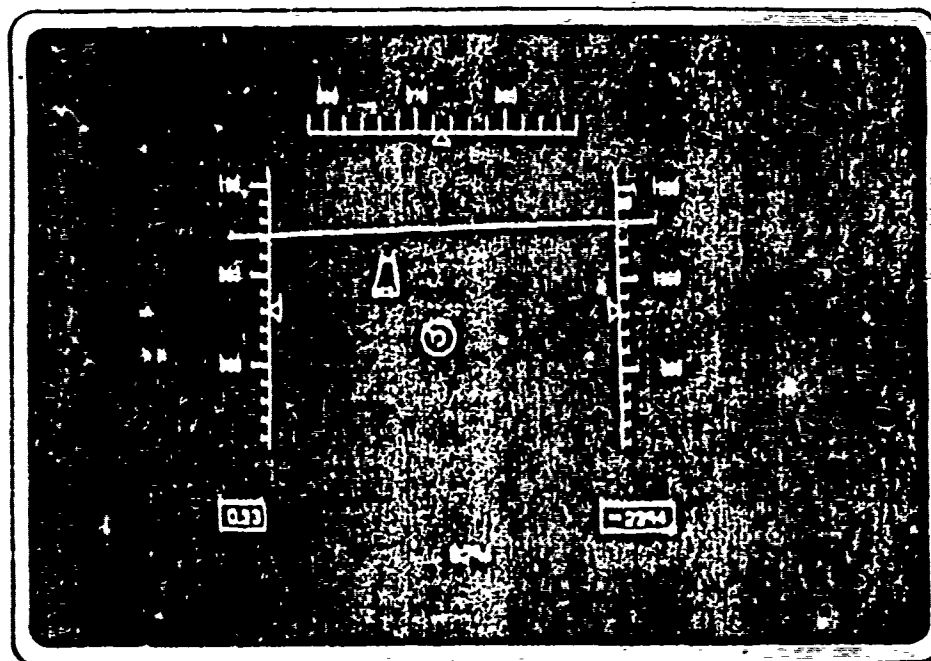
Figure 11.   Candidate Heads Up Display Proposed with Compensatory Display (Angular)

fighter with a HUD. An isometric sidearm controller (as is currently being utilized in the F-16) was installed in the right half of the cockpit, with a thumb button commanding the CCV modes. Thus the fixed base 707 with heads down instruments was converted to an F-16 CCV with a HUD and external scene and modified cockpit interior.

Figure 12 shows the interior of the fixed-base 707 simulator at M.I.T. Previously flight controls were only available to the 707 captain (on the left hand side of the cockpit); controls such as trim button, control wheel, rudder pedals, throttle, landing gear,

Figure 12.   Interior of M.I.T. Fixed-Base 707 Cockpit Simulator.

13-8

speed brakes, flaps and navigation equipment. As Figure 13 demonstrates, the simulator pilot moves these controls to change the states of the aircraft. These mechanical inputs
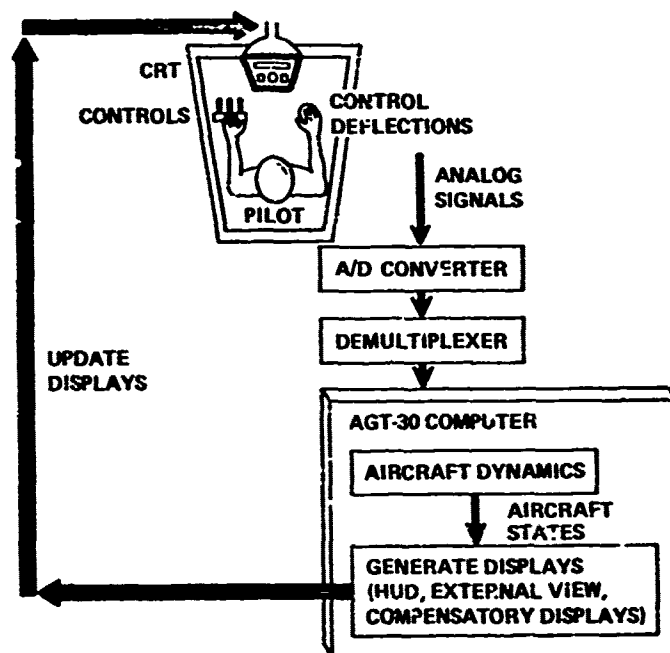
Figure 13. Simulator Operation with AGT-30 Computer.

are converted to electrical analog signals which are then sampled into digital form using an analog-to-digital converter. The signals are demultiplexed and read into the appropriate channels in the assembly language program. The Adage AGT-30 host computer calculates the change in aircraft states utilizing an assembly language 12 degree-of-freedom aircraft model. The AGT-30 updates the aircraft instrument display on the cathode ray tube and the simulation continues. For both the 707 and F-16 CCV simulation the update occurs at least every 1/20 second. The flicker frequency is below the threshold of human visual perception. The present 707 simulator with controls, heads down instruments and a traffic situation display is the product of ten years of research programs at M.I.T.

F-16 CCV Simulator Implementation

The right half of the cockpit was modified to represent the F-16 CCV (Figure 14). An isometric sidearm controller was installed as is currently utilized in the F-16 aircraft. This is interfaced with the Adage AGT-30 computer for flaperon and elevon inputs ("aileron" and "elevator"). Upon completion of the F-16 dynamics programming, the stick gains were adjusted for the proper stick force/roll rate or stick force/g in both the lateral and longitudinal stick input directions. A two-axis thumb button ("coolie hat") utilized in the CCV flight tests was installed on the sidearm stick and interfaced with the AGT-30. Maximum coolie hat inputs corresponded to maximum direct lift and side force levels suggested by the test pilots in the flight test program (approximately 2 g's). Equal authority and gradients existed in the two directions.

Thus the flight controls of interest were well-implemented (stick in right hand, throttle in left hand; flaps, landing gear, etc. within reach). Figure 15 shows the Heads Up Display and external scene the pilot sees on the CRT 21" ahead of his eyes. Therefore in operating the aircraft controls the pilot sees the external view change as well as the readings of the Heads Up Display.

Figure 14.   Right Half of Cockpit Modified to Represent the F-16 CCV With a
Heads Up Display and External View.

Compensatory Displays

Originally the compensatory displays were to indicate just the CCV input which yielded
somewhat encouraging tracking improvements. Later a decision was made to have the compen-
satory arrow and circle represent the vector sum of the direct force modes (coolie hat in-
put) and the wind effects upon the aircraft. Thus the arrow represents the aircraft ac-
celeration. It therefore serves two purposes. By showing acceleration it provides lead
to the pilot in the tracking task. It also provides an additional visual cue to the pilot
when a sudden gust affects the aircraft so that the pilot may respond immediately. Thus
the arrow represents the future position of the velocity vector circle with respect to the
external scene, and aids the pilot with or without wind.

Test Program

The purpose of the test program was to utilize the F-16 CCV simulator to determine
whether the CCV modes do improve tracking performance over the conventional aircraft flight
modes and if the designed compensatory displays do indeed augment CCV tracking performance.
A tracking task was programmed into the F-16 CCV simulator: tracking the aircraft velocity
vector over the runway numbers. A program was written to determine the average error in
tracking (RMS) in degrees $\times$ 1000. Figure 16 shows the instantaneous error ERRT which is
averaged over time (samplings occur every 1/20 second). The performance index or average
RMS tracking error is

$$P.I. = \frac{\int_0^{T_f} (ERRT)dt}{\int_0^{T_f} dt} = \frac{1}{T_f} \int_0^{T_f} [(ERRX)^2 + (ERRY)^2]^{1/2} \, dt$$

A run consists of tracking the velocity vector over the middle of the runway numbers
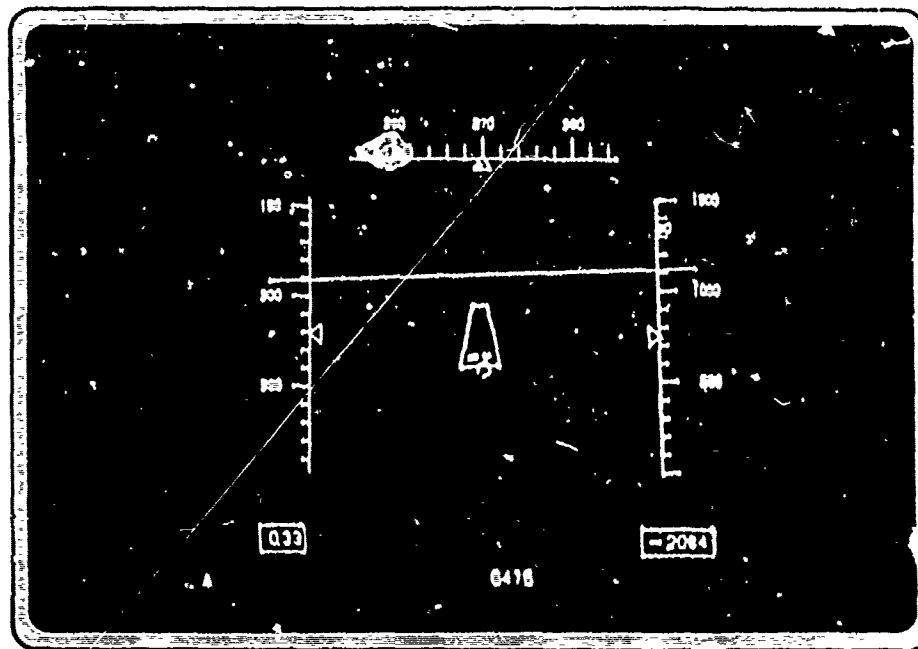
Figure 15. Heads Up Display Overlayed on External Scene.

during a descent from 2500 feet to sea level. At the end of each run the average RMS tracking error was recorded. Three runs were made totalling 6 minutes of tracking for each configuration (with samplings every 1/20 second).
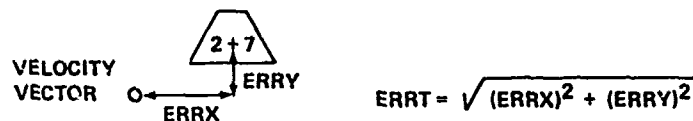

$$ERRT = \sqrt{(ERRX)^2 + (ERRY)^2}$$

Figure 16. Diagram Showing Tracking Error Measure

The four configurations of interest were the basic F-16, F-16 CCV, and F-16 CCV with each of the compensatory displays. Three runs were conducted for each configuration, in the presence of no wind, moderate winds (6.6 kts RMS, peak gust 18 kts) and severe winds (13.2 kts RMS, peak gust 37 kts). The pilots flew the basic aircraft, CCV aircraft, and CCV aircraft with compensatory displays in the presence of various wind levels for approximately 45 minutes for familiarization with the aircraft dynamics to minimize any bias during the testing due to learning. The tests themselves were conducted in several different orders to minimize learning curve bias. Table 1 shows the test run matrix. Displays 1 and 2 were not tested for the no wind case since inputs do not exceed the deadband of the compensatory display. The pilots were not aware of their tracking performance until all the runs in the entire test matrix were completed. No effective comments (positive or negative) were made to the pilots to influence performance. Before quantitative tracking results were revealed, subjective comments were recorded and past flight experience outlined. The quantitative and qualitative results are given in the next section. The pilots did not have to adjust trim or thrust and therefore just utilized the stick and the CCV thumb button during the conduction of the tests. The pilots were instructed that they would be rated purely on how well they tracked the circle of the velocity vector over the runway numbers. The pilots were alone in the simulator during the tests of the various configurations and wind levels. Most of the pilots had combat experience in fighters.

TABLE 1
TEST RUN MATRIX

WIND	CONFIGURATION
No Wind	Basic F-16
	F-16 CCV
6.6 kts RMS	Basic F-16
	F-16 CCV
	F-16 CCV w/Display 1
	F-16 CCV w/Display 2
13.2 kts RMS	Basic F-16
	F-16 CCV
	F-16 CCV w/Display 1
	F-16 CCV w/Display 2

Simulation Results

The results of the test program are given in Table 2. One notes the substantial improvement in tracking performance with CCV modes, and significant increase in performance with the design' displays. Table 2 shows the percent improvement with the CCV modes over the basic a' and percent improvement of the F-16 CCV tracking with the advanced displays for e ...lot. An approximately 40% improvement in tracking ability with the direct force modes .ipares favorably with the gun camera films recorded during the Edwards Air Force Base flight test program.

TABLE 2

SUMMARY OF TRACKING IMPROVEMENTS WITH CCV MODES OVER BASIC F-16 FOR VARIOUS WIND LEVELS (RANDOM ZERO MEAN GUSTS) AND SUMMARY OF IMPROVEMENT IN CCV TRACKING PERFORMANCE WITH COMPENSATORY DISPLAYS (PERCENTAGE)

CONFIGURATION and PERCENT IMPROVEMENT*	PILOT 1	PILOT 2	PILOT 3	PILOT 4	PILOT 5	PILOT 6	MEAN	STANDARD DEVIATION
NO WIND								
CCV OVER BASIC F-16	20.0	57.7	23.7	55.6	48.5	43.8	41.6	14.5
WIND = 6.6 kts RMS								
CCV OVER BASIC F-16	47.9	63.5	54.8	15.1	36.7	30.9	41.5	16.0
F-16 CCV W/DISPLAY 1	7.3	18.7	12.4	18.7	11.8	9.3	13.0	4.44
F-16 CCV W/DISPLAY 2	7.2	15.5	15.2	19.4	13.0	10.5	13.5	3.77
WIND = 13.2 kts RMS								
CCV OVER BASIC F-16	15.5	52.4	50.3	3.1	22.8	36.0	30.0	18.0
F-16 CCV W/DISPLAY 1	7.5	20.4	6.4	15.9	7.8	5.4	9.7	6.29
F-16 CCV W/DISPLAY 2	12.6	17.6	18.4	4.8	6.9	9.8	11.7	5.08

*IMPROVEMENTS IN TRACKING PERFORMANCE WITH DISPLAYS 1 AND 2 ARE REFERENCED TO THE F-16 CCV WITHOUT THE DISPLAYS

A 10-15% reduction of pointing error is observed when the advanced displays are incorporated in the F-16 CCV simulation. There is little difference (1 standard deviation ≃ 5%) in performance improvement between the two displays. Display 2 gives angular predictor information (both displays represent the sum of wind effects and CCV inputs) and display 1 gives magnitude as well as angular information. Since there is little difference between the two displays, magnitude information in this case did not augment performance. This supports the earlier hypothesis that the thumb can sense magnitude information but cannot sense angular information well on the CCV button. It is the additional visual feedback of direction that the pilot uses to improve his tracking performance 10-15%. It is this predictor or lead cue the display gives of where the velocity vector will be superimposed in the next 3/10 second which augments the pilot:CCV aircraft system.

Conclusions

Based on the test program utilizing the fixed-base F-16 CCV simulator with F-16 CCV dynamics, a Heads Up Display with an external view of a numbered runway and horizon, an isometric sidearm stick with a two-axis thumb button to command the direct force modes, and a modified cockpit interior, the following conclusions were reached.

1. In the presence of no wind to moderate winds (6.6 kts RMS), the six pilots utilized the direct force modes to improve RMS tracking ability 40% over that attained with the basic aircraft.

2. In the presence of severe winds (13.2 kts RMS), the direct force modes improved tracking ability approximately 30%. The decrease from (1) is probably due to the fact that large CCV inputs are necessary in severe winds, which cause manual force coupling problems between the thumb button and the sidearm stick.

3. The designed displays improved the tracking capability of the F-16 CCV 10-15%.

4. Subjectively most pilots preferred the arrow display (display 1) over the angular display (display 2); the latter was found to be more distracting.

5. Observing the tracking results, there was no statistically significant difference between the two displays. The angular display gave predictor information for direction; the arrow display gave magnitude and direction information. Thus the pilot primarily used direction information to improve his tracking performance; the additional magnitude information did not improve his performance appreciably. This correlates with the developed hypothesis that the thumb could sense the magnitude of the CCV input well but not its direction. The purpose of the display was to show the direction of the input, which it did. Thus the magnitude cue was already available from the thumb button; the direction is now available from the display.

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EXPERIMENTS USING ELECTRONIC DISPLAY INFORMATION

IN THE NASA TERMINAL CONFIGURED VEHICLE

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SUMMARY

The National Aeronautics and Space Administration Langley Research Center's Terminal Configured Vehicle (TCV) Program, in cooperation with the Federal Aviation Administration (FAA), is pursuing research and technology concept development for airborne systems, operations and procedures that can provide needed improvements and solutions to air transportation problems for conventional civil aircraft particularly for the 1980-2000 time period. Specifically, it is to provide the airborne systems capability which can lead to increased airport and runway capacity, increased energy efficient terminal area operations, reduced weather dependence with safety and reduced community noise by use of improved flight procedures. This paper describes several research activities and experiments within the TCV Program having as one of their objectives the definition of pilot electronic display information requirements.

INTRODUCTION

The National Aeronautics and Space Administration (NASA), Langley Research Center, Terminal Configured Vehicle (TCV) Program has been established to conduct research necessary to identify, evaluate, and demonstrate flight systems and flight management technology concepts that will improve the efficiency of conventional takeoff and landing (CTOL) aircraft operations in high density terminal areas with reduced weather minima. Terminal area problems addressed in the program include safety; weather effects; congestion and resulting loss in productivity caused by delays, diversions, and schedule stretchouts; energy management; and noise (refs. 1 and 2).

The TCV B-737 aircraft is one element of extensive analysis, simulation, flight, and airport experimental facilities located at the Langley and Wallops Flight Centers (ref. 3). Major attention is being focused on the avionics, displays, airborne systems, and interfaces between the pilot and air traffic control (ATC) systems. Attention is also being paid to the efficient transfer of information between the pilots, on-board systems and the traffic control system and an improved distribution of work between the pilots and on-board systems to optimize the pilots' ability to function as the flight manager in the future environment.

Activities in the past have included modifications to the advanced displays and automatic flight controls in the NASA TCV B-737 aircraft which enable close-in curved approaches through landing using the MLS, and demonstration of the benefits of this combined capability to the International Civil Aviation Organization (ICAO). Present activities are dedicated to experiments which further characterize efficient descent and approach paths, and use MLS, RNAV, precision path control, and on-board displays to improve airspace, runway, and crew utilization. Future research will extend this work to the multi-aircraft operating environment and address various distributed-management and crew-information options which could improve system capacity in the 1990's ATC environment (ref. 4).

This paper will present results of research experiments having as one of their objectives pilot display information requirements and visualization techniques for electronic display systems. The paper will be divided into sections dealing with display related piloting tasks in flight controls for approach-to-landing, flight management for the descent from cruise, and flight operational procedures considering the display of surrounding air traffic. Planned research of advanced integrated display formats for primary flight control throughout the various phases of flight will also be discussed.

TEST AIRPLANE AND EXPERIMENTAL SYSTEMS

A cut away view of the aircraft illustrating the palletized research installation aboard the test airplane is shown in figure 1. Major components consist of a standard forward cockpit, an aft flight deck (AFD) for research, navigation and guidance pallets, flight control computers, and a data acquisition system. The aircraft is equipped with digital, integrated navigation, guidance, control, and display systems which can be readily reprogrammed for research purposes. A simplified block diagram of the experimental avionics system used for flight research is shown in figure 2. The system functions are controllable and variable through software, and the hardware is readily accessible for modification or repair.

The two-man aft flight deck arrangement is shown in figure 3. The center area of the cockpit is seen to resemble a conventional B-737 cockpit, whereas the area

immediately in front of the pilot and co-pilot have been opened up by removing the wheel and column and replacing them with panel mounted controllers. The placement of these controllers permits full view of the flight displays. Both pilots are similarly equipped with electronic vertical and horizontal situation displays (EADI, EHSI) and the Navigation Control and Display Unit (NCDU), which includes a navigation data display and a keyboard for communication with the navigation computer system. The pilot has display mode panels to call stored airport or other information from computer memory. He can similarly reject or erase information depending on its importance during each phase of his flight. The other facet of research flight deck operations is the Control Mode Panel located in the center of the glare shield. In this system either pilot can operate the airplane through either of two computer augmented manual control modes or five automatic modes.

The EADI display provides basic attitude, horizon, and approach path error information. Additional information including speed error, flightpath and track, altitude, and a computer drawn perspective runway with extended centerline have been integrated into the display format. The EADI symbology is explained in figure 4. The EHSI, illustrated in figure 5, is a pictorial navigation display to provide the pilot with accurate aircraft situation information relative to the guidance path desired (either INS or MLS RNAV derived), flight plan waypoints, and geographic points of interest such as airfields, mountains, and VORTAC's. The dotted track select line is a tentative new track and becomes solid when acquired in manual flight or accepted through the NCDU for automatic flight. In the illustration the desired horizontal flight path is displayed as a solid line connecting waypoints. The curved trend vector shown emanating from the nose of the aircraft symbol consists of three dashes indicating future position at 30-, 60-, and 90-second intervals. Only a 30-second trend vector is displayed with the 1 n. mi. scale. A rectangular box, just beyond the waypoint SOUND, indicates the scheduled along-path position during 4-D (time navigation) operations, with the dots ahead of it indicating future scheduled positions at 30, 60, and 90 seconds. The time box location of figure 5 provides the pilot with an indication of his scheduled time and flightpath position errors.

Magnetic track is indicated at the top of the EHSI. The operating modes of the two EHSI's (pilot and first officer) are independent; i.e., one may be operated in the north-up mode (for route visualization) and the other in track-up (preferred for navigation). The EHSI's may also be operated with different map scales or options. The six map scales provided are 1, 2, 4, 8, 16, and 32 n. mi./inch, and the one selected is displayed in the lower left corner of the EHSI. The altitude/range symbol, an option when in the track-up mode, consists of an arc some distance ahead of the aircraft symbol and represents that location at which the aircraft would reach the reference altitude, selected via the control mode panel, if the current flightpath angle is maintained. In the lower right corner of the EHSI are displayed the ground speed (GS) in knots, the mode of navigation (in this case inertial with single DME update, IDX), and the wind velocity and direction. When in the MLS RNAV mode, the letters AMX (for air data, MLS update) would appear.

There are 12 pages of display information that the pilot may select through the NCDU keyboard. This display is used by the pilot to enter or change initial flight conditions and flight plans, examine current navigation data pages, select display options, check experimental system status information, and recall stored navigation data. Figure 6 is a drawing of the display portion of the NCDU and illustrates the type of information presented on one of three navigation data pages.

RESULTS AND DISCUSSION

Approach-to-Landing

The results of an initial TCV piloted simulation effort showed that the addition of a perspective runway image and relative track information to a basic EADI format improved flightpath tracking performance during a straight-in approach-to-landing using standard manual control (ref. 5). In addition, the integration of this information with the display of flightpath angle allowed the immediate assessment of the current situation (of the aircraft with respect to the runway) and any control corrections necessary. Following the simulation, a flight test evaluation was conducted to assess the benefits of the integrated display format coupled with a velocity vector control mode for the approach task. The results agreed with the earlier simulation results and compared favorably with Category II flight-director performance criteria (ref. 6). This display format had been used previously to monitor numerous automatic approaches and landings conducted as part of the NASA/FAA Microwave Landing System (MLS) flight tests and demonstrations (ref. 7). As flight testing continued, however, pilot desires surfaced for an improved velocity vector control mode with accompanying display information changes, especially when flying in turbulent atmospheric conditions.

The development of improved longitudinal and lateral velocity vector control modes for the TCV B-737 is discussed in reference 8, and the results of a simulation evaluation of the longitudinal mode is presented in reference 9. The desire of the pilots to use flightpath angle as primary information required the further development and tailoring of the longitudinal control mode. The display of anticipatory flightpath information, to allow early assessment of the pilot control action, was considered necessary in turbulence for precise approach control with low physical workload. Requirements for total system response from pilot control inputs were defined and the resulting longitudinal control mode with forward loop column position integration was developed.

Reference 8 contains a detailed discussion of the control response shaping that was accomplished to satisfy the pilot's desired system response. An integrated control/ display approach was taken in developing the improved system. A drawing of the display format illustrating the additional display information is shown in figure 7. The reference (pilot commanded) flightpath angle information can be seen as dashed line wedges. Current or actual flightpath angle information is regarded as primary flight information by the pilots and was retained in the shape of the solid line wedges. The points of the actual flightpath symbols were removed so that the pilot could easily assess the value of each parameter and how well the airplane's actual flightpath tracks the desired reference flightpath angle.

The simulation tests consisted of a tracking task that required the pilot to make step changes in flightpath angle. The movable pitch reference line, seen in figure 7, was used as a target and driven to different values as a function of time. The pilot was required to track the target to the best of his ability. Another task used in the simulation tests was an approach-to-landing task on a 3° glideslope, including flare and touchdown. The approaches were conducted in calm, turbulent, and wind shear conditions. A baseline and various levels of improved systems were studied in simulation, and a statistical treatment of the data was made.

The results of the tracking and approach to landing task data show a reduction in overall mean tracking errors with the control/display system improvements. A 50% reduction in pilot control input activity was also noted with this system during the approach-to-landing task. A complete discussion of the statistical examination of the simulation data is presented in reference 9.

An improved lateral control mode concept with curved ground track control has also been developed (ref. 8). The design of this control mode requires that the pilot's lateral control input be used to develop not only a bank angle command but also a corresponding track outer loop command. Considering the lateral path capture task and especially the close-in curved approach task, this control mode reduces pilot workload by maintaining a constant radius ground track. In effect, this reduces the task to one under a no-wind condition.

The display aspects of this design have brought about the presentation of a reference (pilot commanded) roll attitude shown in figure 7, in a dashed line format and stabilized the horizontal trend vector presentation on the EHSI (fig. 5), especially in turbulence. For small, precise track changes during final approach, the display of reference track angle (fig. 7) has been found to be very helpful to the pilots. The display of the reference or pilot commanded values of flightpath and track angle information, coupled with the small control input capability through a trim button, has allowed the pilot to make precise reference changes to those parameters. Pilot comments using the system in simulation and flight have been most favorable.

Another desired feature of this control mode is a simplified decrab maneuver capability. The system has been designed to require rudder pedal input only to establish a proportional decrab angle while the pre-established ground track is maintained.

Flight Management - Descent from Cruise

The Federal Aviation Administration has developed an automated time-based metering form of air traffic control for arrivals into the terminal area called local flow management/profile descent (LFM/PD). The LFM/PD concept provides fuel savings by matching the airplane arrival flow to the airport acceptance rate through time control computations and by allowing the pilot to descend at his discretion from cruise altitude to the metering fix in an idle thrust, clean configuration (ref. 10).

Numerous studies have illustrated the benefits and the feasibility of time navigation in achieving the maximum landing rate (ref. 11). The initial ground systems work has been laid for time-based metering and definite progress is being made. The NASA is concerned with the airborne side of the problem. The pilot's display and control requirements for both the manual and automatic modes for this task must be determined if the total system is to work and the maximum benefits are to be gained.

As a first attempt to better understand the time related display and control task in the cockpit, a flight experiment was conducted where the pilot was required to deviate from an established time slot and capture one that was 6 minutes behind. This task was established to simulate a situation where the flow to the airport is disrupted and an attempt to absorb the delay is handled by a holding pattern turn at high altitude. Considering that under these conditions the controller will be handling numerous aircraft and flightpath changes, it may be difficult for the controller to direct each airplane out of its holding pattern to make good a new time schedule. The objective of the test then was to examine the ability of the pilot to perform this task with the on-board displayed information.

The flight originated at Langley Research Center with high altitude routing and terminated with an ILS landing at Norfolk, a total distance of 259 n. mi. The flight had a scheduled landing time. Immediately after takeoff from Langley the aircraft was placed under 4-D automatic control. The major portion of the flight was accomplished automatically except for a maneuver to illustrate manual control capability in the 4-D mode as discussed in reference 12.

During the flight leg from waypoint LVL to RMT, as illustrated in figure 8, a 6-minute delay in scheduled arrival time was simulated. Using the velocity vector control mode (holds track and path angle) the pilot manually entered a holding pattern, then recalled the appropriate NCDU flightpath page when on the "outbound" track and entered the new arrival time at RMT in the navigation computer. This change initiates the proper computations through all flight legs and resets the time box (current scheduled position). Since the EHSI shows only magnetic track, it can be seen in figure 9 that the velocity vector control mode held track very well against the existing 90 kt direct crosswind from the west. It is obvious that during the turns considerable drift occurred, necessitating an intercept angle inbound. Although this was the first such maneuver from the pilot, he was able to make use of the predictive trend vector time dashes ahead of his aircraft symbol and the rescheduled time box with the time dots ahead of it, to judge the start of his inbound turn and the maneuver to reacquire the time box. Other aids to the pilot for time control are the flight acceleration command bar (fig. 4) for thrust management purposes, and a readout of time error and time error per minute, separation or closure, on the NCDU display shown in figure 6. Figure 9 shows that the pilot was able to close on the inbound track only 5 seconds behind the time box. He continued closing until he again coupled with the automatic mode 1.5 seconds behind the time box. The aircraft arrival at touchdown (rescheduled) was within 5 seconds of that planned.

An important conclusion is that the displays and velocity vector control mode give the pilot an alternative method of accurate navigation and control, which permits him quick reaction time for an occasion such as the change in arrival time request, or avoiding a threat. The track angle hold mode gave him time on the outboard leg to reprogram the computer to the readjusted time for further automatic flight. Without the displays he would not have been able to execute this type of repositioning pattern with any degree of expediency or precision on his own. It is felt that this control/display capability is very necessary for the widespread success of time navigation in the future environment.

Following this experiment, flight tests using a flight management descent algorithm were conducted in the Denver, Colorado, LFM/PD ATC environment (ref. 13). The purpose of these flight tests was to quantify the accuracy of the airplane's descent algorithm and to investigate the compatibility and pilot acceptability of an airplane equipped with time navigation capability in an actual ATC environment.

The flight management descent algorithm computes a five-segment descent profile (fig. 10) between an arbitrarily located entry fix to an ATC defined metering fix. A sixth segment from the metering fix to the next fix (specified by ATC and called the aim point) is also generated. Time and path guidance descent information based on these six segments is provided to the pilot. The first officer initiates the path computations through the keyboard using the NCDU display. An additional ATC clearance page format was developed for this experiment (fig. 11). Once the desired metering fix arrival route is entered, the required pilot inputs are displayed; ATC assigned time or pilot desired speed schedule, winds, pressure, temperature, and weight. When an assigned metering fix time is entered that cannot be met when a limit operational descent speed is used in the profile computation, then an appropriate "early or late by" time message is announciated at the bottom of the NCDU display.

The display of information for the pilot during these tests was provided on the EADI, EHSI (map display), and on the NCDU. Two options of the EADI display information used for lateral and vertical path navigation on these flight tests were the vertical and lateral course deviation indicators and the star and flightpath angle wedges (fig. 12). The flightpath angle wedges used with the star display represent the inertially referenced flightpath of the airplane. If the airplane flightpath angle and track angle are adjusted so that the flightpath angle wedges center directly on the star, the airplane will be flying directly to the waypoint.

Figure 13 shows a drawing of the EHSI display operated in a track-up mode. This display is a plan view of the desired route and optionally displayed figures such as radio fixes, navigation aids, airports, and terrain features drawn relative to a triangular airplane symbol. The range/altitude arc was used on the descent profile during these tests by setting the reference altitude to the programmed altitude to the next waypoint. Then the pilot would adjust the flightpath angle of the airplane so that the arc would lie on top of the next waypoint displayed on the EHSI. This would result in the airplane crossing the next waypoint at the programmed altitude.

Between the top-of-descent and the metering fix waypoint, the airplane was flown at idle thrust and the use of speed brakes was not permitted. The captain used path guidance on the EHSI display and the lateral path deviation indicator on the EADI for lateral path guidance. For vertical guidance, he used the star and flightpath angle wedges on the EADI and the range altitude arc on the EHSI display. It was the responsibility of the first officer to select the desired altitude for the range/altitude arc option so that the captain could devote his full attention to flying the airplane. The captain would anticipate leveling the airplane for the programmed altitude at the bottom-of-descent waypoint with reference to a conventional barometric altimeter and then would proceed to the metering fix.

The research flights demonstrated that time guidance and control in the cockpit was acceptable to the pilots and air traffic controllers. The flight data indicates that airspeed error of the airplane over the metering fix had a mean value of 0.27 knots and

a standard deviation of 6.5 knots. Time error over the metering fix had a mean value of 2.5 seconds and a standard deviation of 6.9 seconds.

Flight tests having similar results were conducted in the LFM/PD environment of the Dallas-Fort Worth terminal area. using the Lockheed-California Company L-1011 test airplane, to evaluate the performance potential of a Flight Management System which was modified by Lockheed (under NASA contract) to incorporate a time navigation capability to control terminal area metering fix arrival time during fuel efficient descents from cruise altitude. The results of these flight tests were similar to those of the Denver flights and will be reported in a near-future NASA Contractor Report.

Display of Surrounding Air Traffic

As part of a joint NASA/FAA effort, Cockpit Display of Traffic Information (CDTI) studies are in progress to evaluate the capabilities, benefits, and liabilities of providing this information to the pilot in the future ATC environment. Items to be addressed are the means for providing data of sufficient accuracy and frequency, the role of aircrew and controllers in the ATC process, evaluation of performance and accuracies to determine effects on capacity, controller and aircrew workload, and safety.

Potential benefits of the CDTI fall into the general areas of improved capacity, efficiency, and safety. Proponents of the CDTI believe its application in the ATC process can improve terminal area capacity by allowing for reduced aircraft separation, efficient merging, and general improvement in aircraft traffic control and crew execution. By providing sufficient information, collisions may be avoided through advance indications of traffic conflicts wherein the air traffic controller and aircrew can make course changes to resolve the conflict. The display may also serve as backup for certain ATC system failures.

Concerns for the use of the CDTI are that it may result in less efficient operations, with the aircrew challenging the air controller, increasing workload and possibly unilateral action resulting in less control and safety. The effect of CDTI usage on the air traffic controller and aircrew operational procedures and workload must be determined to judge its utility in the ATC system.

One of the major issues is the role of the CDTI in the overall ATC process. Should its use be passive as in a monitor role, where its application is to provide the aircrew with independent information on traffic for providing assurance and an error detection capability? Or, alternatively, can the CDTI be applied in an active role, utilizing the traffic display to control in-trail spacing and lateral separation and to resolve traffic conflicts? Ultimately, if the CDTI is a useful approach for improving the ATC operations. its application may be a compromise between the two roles described above. The aircrew will be able to utilize the CDTI to execute certain functions that are best controlled from the air, with knowledge of the controller, who has the overall ATC responsibility.

The TCV program fixed-base simulator was used to conduct an experiment involving the evaluation of cockpit display of traffic information. The experiment was conducted using taped time-dependent, non-interactive traffic in an approach-to-landing situation with two levels of pilot control: 3-D automatic and the velocity vector control mode. Speed control via manual speed selection and autothrottle was used in all tests (path stretching was not allowed for maintaining separation between aircraft). The results presented in reference 14 indicate that reasonable approach task performance can be maintained when traffic information is displayed on an electronic map for both merge and follow type situations. A trend toward reducing separation where large gaps existed was observed. This gives some evidence of "electronic VFR" operation. Overall, the results are favorable toward presentation of traffic information during fixed path, descending, decelerating approaches.

During the CDTI simulation experiment an oculometer measuring eye look point was used to determine pilot visual scan patterns with and without traffic information on the EHSI. Long straight-in and close-in, curved, descending instrument approaches were made in NASA's fixed-base TCV simulator. The pilot either manually controlled the simulator or monitored the automatic system control of the simulated aircraft during the approach. Tests were performed with and without the display of traffic. The results (ref. 15) indicate that the pilots' use of the EHSI increased for the manually controlled close-in, curved, descending approach compared to the conventional straight-in approach. When operating as a monitor of the automatic system, the pilot scanned around more with less attention devoted to the EADI. The pilots preferred the manual mode because it kept them in the control loop. The addition of displayed traffic to the EHSI increased the pilots' use of the EHSI with a corresponding reduction in his use of the EADI.

This addition of traffic information to the EHSI increases the pilots' attention to this display by 11 to 17% with the greatest shift in attention occurring for the automatic control cases. A secondary result of this experiment shows that the pilot uses the EHSI considerably more for the curved approach case than for the straight-in approach case with or without the display of traffic symbology. It was also noted that the pilot's pupil diameter increased during the landing flare indicating a higher stress level even though the tests were conducted in fixed-base simulators. This experiment has been repeated in flight to obtain data for simulation validation and to determine the effects of actual flight operations. Preliminary review of the flight data indicates a high degree of correlation between simulation and flight results. Final results of these flight tests will be reported in a near-future NASA report.

A TCV B-737 flight experiment has been conducted to evaluate the presentation of coded traffic symbology on the EHSI. The results of this experiment are presented in references 16 and 17. The primary objective of this study was to assess the benefit of coded traffic symbology and to obtain an initial assessment of the impact of workload on pilot ability to monitor the traffic display using simulated traffic in a flight environment. The tests consisted of curved, descending, decelerating approaches, flown by research pilot flight crews. The traffic scenarios involved both conflict-free and blunder situations.

Figure 14 is an illustration of the changes to the basic EHSI display symbology and an explanation of the various coding used for the surrounding traffic. Figure 15 is a photograph of the displays taken during a CDTI flight. The use of the coded traffic symbology and the defined approach paths for the aircraft can be seen on the EHSI. Information presented on the EADI and NCDU can also be seen. The displayed traffic was synthesized via magnetic tapes and played into EHSI to simulate various traffic scenarios, with and without conflicts.

Subjective pilot commentary was obtained through the use of a questionnaire and extensive pilot debriefing sessions. The results of these debriefing sessions group conveniently under either of two categories: display factors or task performance. A major item under the display factor category was the problem of display clutter. The primary contributors to clutter were the use of large map scale factors, the use of traffic data blocks, and the presentation of more than a few aircraft.

In terms of task performance, the coded traffic symbology was found to provide excellent overall situation awareness. Additionally, the pilots expressed a willingness to utilize lesser spacing than the 2.5 mile separation prescribed during these tests assuming the wake vortices would not be a problem. Results of pilot scan and dwell time measurements obtained during these flight experiments will be reported later.

NASA and FAA are developing additional test scenarios to address the various roles and application of CDTI in projected ATC environments, with TCV aircraft flight tests planned for the NASA-Wallops Flight Center and FAA-NAFEC. A brief summary of the joint NASA-FAA CDTI effort is presented in reference 18.

Advanced Display Formats

Significant advances remain to be made in the primary flight display area if we wish the airplane/pilot system to routinely execute vertical and time navigation terminating in close-in curved approaches within a Microwave Landing System environment. The previously cited automatic and manual flight results were obtained with the pilots scanning both the EHSI and EADI for the required set of information prior to the final approach segment. As the low altitude portion of the curved flight was extended and the final approach shortened, the precision, the guidance accuracy, and the information available to the pilots on their display became more critical. The displays were adequate, and acceptable to the pilot, for the curved approach task to the short final, but the need for an integrated pictorial presentation was determined.

The reproduction of electro-mechanical indicator information onto electronic displays will not solve the piloting problem of integrating pieces of information into a clear mental image of his flight condition. Flight path display formats must be developed that integrate attitude, flight path, speed, relative position, and pertinent numerical information into an easily understood perspective display of the aircraft's flight situation.

Two flight path display formats currently being addressed are the path-in-the-sky concept shown in figure 16 and the tunnel-in-sky concept shown in figure 17. The path-in-the-sky display format is designed to integrate information concerning attitude, kinematic performance, navigation, and path prediction (ref. 19). The tunnel-in-sky integrates situation and predictor information into one format (ref. 20). Both formats are aimed at presenting the pilot with a 3-D perspective image of path situation and prediction. Simulation experiments with both the path and tunnel concepts will be conducted in the near future to complete the format designs for adaptability to all phases of flight.

CONCLUDING REMARKS

The NASA TCV program is vitally concerned with the aircraft's operational capability in the future air traffic system. This program involves the capability of the aircraft, its system, and flight crew to improve the efficiency and safety of the terminal area in a more demanding weather environment than present. It also includes the capability of the airborne system to work synergistically with the air traffic control system to improve flight efficiency in the traffic flow with reduced problems for both the aircrew and ground controller.

The studies conducted to date that address the integration of flight information in the cockpit represent only a small but well defined portion of the system problem. It has been concluded that the mere reproduction of present or similar instrument indicator information onto electronic displays will not solve the piloting problems envisioned in the future. The research and development of innovative pictorial display formats coupled with flight control, navigation, guidance, and performance considerations must be

aggressively pursued. The current experiments described in this paper are specific planned steps in the overall attainment of the program goals.

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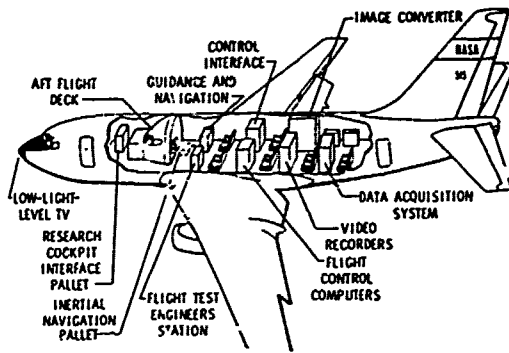
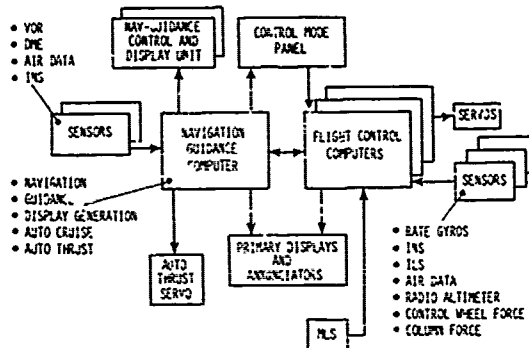Figure 1. - NASA TCV B-737 research airplane internal arrangement.

Figure 4. - EADI display information.

Figure 2. - NASA TCV B-737 experimental systems configuration.
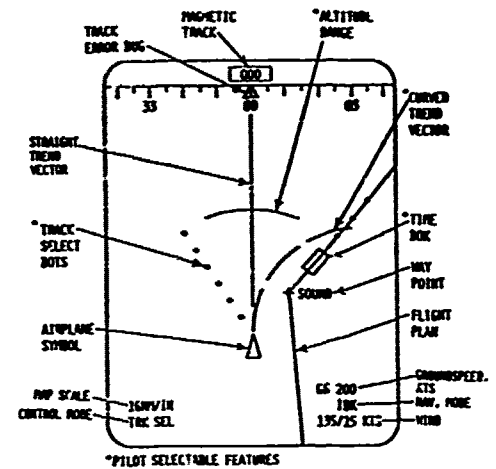

Figure 5. - EHSI display information.

Figure 3. - Aft flight deck display arrangement.
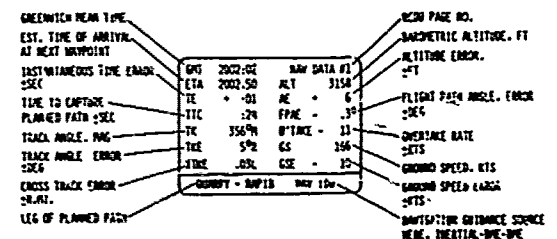
Figure 6. - NCDU display of navigation data.
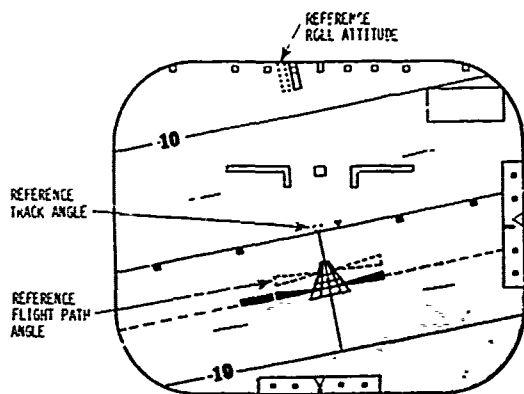
Figure 7. - EADI with reference flight
inf. mation.

Figure 10. - Vertical plane geometry associated
with LFM/PD algorithms.

Figure 8. - NASA TCV B-737 time navigation
task.
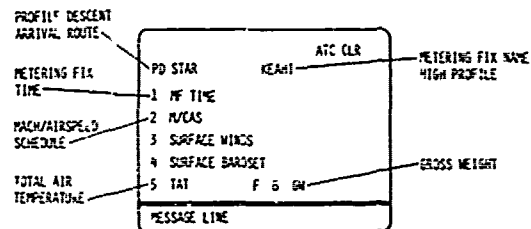
Figure 11. - NCDU ATC clearance page for LFM/PD
flight test.

Figure 9. - Hold pattern, capture of time box.
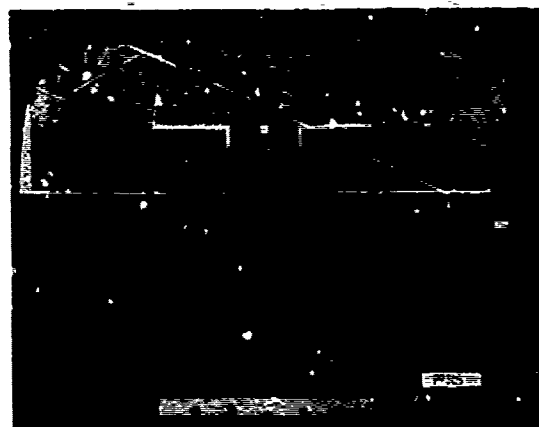
Figure 12. - EADI display information for LFM/PD
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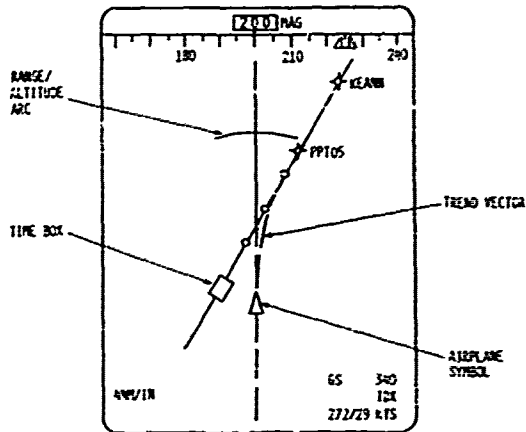
Figure 13. - EHSI display information for LFM/PD flight test.
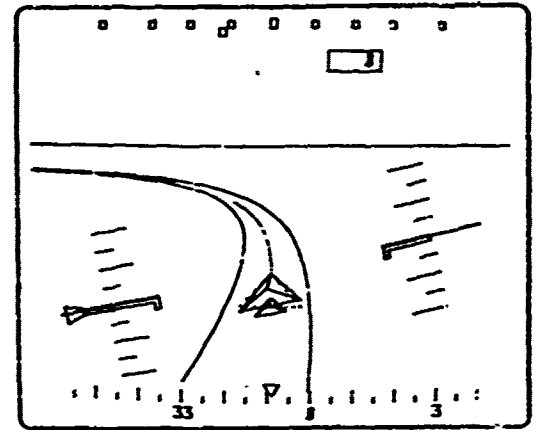
Figure 16. - Path-in-sky display concept.

Figure 14. - CDTI information coding.

Figure 17. - Tunnel-in-sky display concept.

Figure 15. - TCV display system information during CDTI tests.

REPORT DOCUMENTATION PAGE

1.Recipient's Reference	2.Originator's Reference	3.Further Reference	4.Security Classification of Document
	AGARD-AG-255	ISBN 92-835-1371-1	UNCLASSIFIED

5.Originator	Advisory Group for Aerospace Research and Development North Atlantic Treaty Organization 7 rue Ancelle, 92200 Neuilly sur Seine, France

6.Title	ADVANCEMENT ON VISUALIZATION TECHNIQUES

7.Presented at	

8.Author(s)/Editor(s) Various Edited by Professor Walter M.Hollister	9.Date October 1980

10.Author's/Editor's Address Department of Aeronautics and Astronautics (Bldg 33.177) Massachusetts Institute of Technology Cambridge, MA 02139, USA	11.Pages 226

12.Distribution Statement	This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13.Keywords/Descriptors

Human factors
Flat panel displays technology
Helmet-mounted display
Cockpit display

14.Abstract

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This AGARDograph was prepared at the request of the Guidance and Control Panel of AGARD.

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